

UNIVERSIDAD POLITÉCNICA DE MADRID
Escuela Técnica Superior de Ingeniería Aeronáutica y del Espacio



Initial sizing methodologies for multi- role fixed-wing remotely piloted aircraft

DOCTORAL THESIS

Submitted for the degree of Doctor by:

Álvaro Gómez Rodríguez

Master of Science in Aeronautical Engineering

Madrid, 2025



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Under the supervision of:
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Abstract

Remotely Piloted Aircraft Systems (RPAS) are currently undergoing a remarkable expansion within the field of aviation. Their particular characteristics with respect to traditional manned aircraft enable a very distinct set of applications, and at the same time, result in contrasting design features when compared to them. In view of their potential, the deployment of RPAS has accelerated and their number is increasing exponentially, with the missions being undertaken by them becoming ever more varied and complex. Furthermore, the rapid growth in the interest and presence of these aircraft within the aviation paradigm has led to an intense rulemaking activity, through which Aviation Regulatory Authorities are currently developing airworthiness regulations applicable to RPAS at an accelerated pace so as to ensure their safe integration in the airspace, which is expected to further allow to leverage their potential.

Within this context, it is fundamental to develop original design methodologies that can aid in the configuration synthesis and initial sizing of Remotely Piloted Aircraft (RPA), which is the air vehicle component of the system. Thus, the main objective of this thesis is to develop new conceptual design methodologies for the first stages of fixed-wing RPA design. These kind of methodologies are characterised by the use of rapid procedures that can be employed to explore an expansive design space, so as to select the most promising candidate configurations, which would then be passed over to the preliminary design stage, where higher fidelity approaches are employed, at the cost of greater computational effort.

Firstly, a thorough literature review of current RPA design procedures is conducted, with a particular focus on aircraft computerised design environments, which allows to detect the most relevant disciplines for the different design stages and to identify key gaps within the state-of-the-art. In view of this evaluation, a suite of interconnected conceptual design approaches is developed in this thesis, focusing on three main areas: statistical approaches, airworthiness-based design methodologies, and sizing according to multi-role integral performance requirements.

With respect to the first area, a database of RPAS is compiled, and key design trends are extracted, both using the traditional technique of regression analysis, as well as a novel approach based on the statistical methodology of factor analysis, which allows to extract underlying design trends and their connection with observable variables. The results from this line of work show that novel empirical expressions with adequate statistical significance for the conceptual stage can be extracted, which can be used for rapid sizing of new RPA.

Regarding the airworthiness-based design approaches, after conducting a thorough review of applicable regulations for RPA, a procedure is developed for the systematic extraction of certification requirements applicable for RPA, as well as their integration within initial sizing methodologies. It is then seen that airworthiness requirements constitute crucial restrictions in the design space. The results are greatly dependent on the RPA category, since this affects the regulations applicable to each case.

Finally, a design methodology based on the estimation of multi-role integral performances of RPA is developed. Its main objective is to perform the sizing of an aircraft which can simultaneously comply with the requirements of several missions, as defined in the initial requirements. This enables to leverage the multi-role potential of RPA, as it is increasingly common that the same air vehicle is deployed in very distinct applications.

The combined use of these three approaches leads to an overall conceptual design methodology which enables to tackle initial sizing activities of multi-role RPA attending to certification constraints and leveraging key potential features of these aircraft.

Resumen

Los sistemas de aeronaves pilotadas por control remoto (RPAS) están experimentando una notable expansión. Sus características particulares en comparación con las aeronaves tradicionales pilotadas a bordo permiten desarrollar aplicaciones muy diferentes, y a la par conducen a características de diseño distintivas. Recientemente se ha acelerado el despliegue de estas aeronaves, siendo sus misiones cada vez más variadas y complejas. Además, su rápido crecimiento está resultando en una intensa actividad de reglamentación, a través de la cual las Autoridades Reguladoras de Aviación están desarrollando normativa de aeronavegabilidad para RPAS, con el fin de asegurar su integración segura en el espacio aéreo, lo cual se espera que pueda permitirles explotar aún más su potencial.

En este contexto, resulta esencial el desarrollo de metodologías novedosas de diseño que puedan apoyar la síntesis de la configuración y el dimensionado inicial de las aeronaves pilotadas por control remoto (RPA), que es el componente de vehículo aéreo del sistema. Con ello, el principal objetivo de esta Tesis consiste en el desarrollo de metodologías originales de diseño conceptual de RPA de ala fija adecuadas para sus primeras fases de diseño. Este tipo de técnicas se caracterizan por el uso de procedimientos rápidos compatibles con la exploración de un extenso espacio de posibles diseños, para así seleccionar la configuración más prometedora. Esta posteriormente pasaría a la etapa de diseño preliminar, en la que se emplearían métodos de mayor precisión, si bien requiriendo mayores recursos computacionales.

En primer lugar, se lleva a cabo una revisión de la literatura, prestando especial atención a las herramientas computacionales de diseño de aeronaves. Esto permite identificar las disciplinas más relevantes para cada etapa de diseño, y además detectar nichos de investigación. A la vista de este análisis, en esta Tesis se acomete el desarrollo de un conjunto de metodologías de diseño conceptual interrelacionadas, centradas en tres áreas principales: enfoques estadísticos, metodologías de diseño basadas en aeronavegabilidad y dimensionado basado en requisitos de actuaciones integrales multi-rol.

En cuanto al primer ámbito, se elabora una base de datos de RPAS para extraer de ella tendencias de diseño, usando tanto la técnica tradicional de análisis de regresión, como un enfoque novedoso basado en el análisis factorial, que permite extraer tendencias latentes de diseño y revelar su conexión con variables observables. Se muestra que es posible extraer nuevas relaciones empíricas con una significación estadística adecuada, y que estas pueden ser usadas para el dimensionado rápido de nuevos RPA.

Respecto a las metodologías de diseño basadas en aeronavegabilidad, tras llevar a cabo una revisión detallada de normativa aplicable, se desarrolla un procedimiento tanto para

la extracción sistemática de requisitos de certificación aplicables a estas aeronaves, como para su integración en metodologías de dimensionado inicial. Se observa que los requisitos de aeronavegabilidad suponen restricciones de diseño críticas en el espacio de diseño. Los resultados dependen en gran medida de la categoría del RPA, ya que de esta depende la normativa aplicable a cada caso.

Finalmente, se elabora una metodología de diseño basada en la estimación de actuaciones integrales multi-rol de RPA. Su objetivo principal es llevar a cabo el dimensionado de una aeronave que cumpla simultáneamente con los requisitos de distintas misiones definidas en sus requisitos iniciales. Esto permite explotar el potencial multi-rol de los RPA, al ser frecuente que el mismo vehículo se emplee en muy diversas aplicaciones.

El uso combinado de estas tres técnicas conduce a un método conjunto de diseño conceptual que permite abordar las actividades de dimensionado inicial de RPA multi-rol con especial atención a requisitos de certificación y permitiendo explotar capacidades clave de estas aeronaves.

Table of Content

<i>Abstract.....</i>	<i>iii</i>
<i>Resumen.....</i>	<i>v</i>
<i>Table of Content</i>	<i>vii</i>
<i>List of Figures</i>	<i>xiii</i>
<i>List of Tables.....</i>	<i>xxv</i>
<i>Abbreviations and acronyms</i>	<i>xxix</i>
1. INTRODUCTION	1
1.1. Current state and outlook of RPAS	7
1.2. Outstanding characteristics of fixed-wing RPA.....	11
1.3. Current challenges in RPA conceptual design.....	14
1.4. Research motivation and objectives	20
1.5. Thesis contents, organisation and structure	25
1.6. Research results and collaborations.....	30
2. RPA DESIGN THEORETICAL BACKGROUND AND STATE OF THE ART	33
2.1. Aircraft design theoretical background.....	33
2.1.1. Analysis and synthesis approaches	35
2.1.2. Phases of the design process and their usual methodologies.....	37
2.1.3. Generic Design Methods (GDM) and Ad-hoc Developed Design Methods (AADM)	48
2.1.4. Computerised design environments	51
2.2. Literature review of current RPA design approaches: main trends and current gaps.....	57
2.2.1. Purpose and motivation of the review	58
2.2.2. Review approach, scope and boundaries	61
2.2.3. Definition of topical areas to group design approaches.....	63
2.2.4. Review results and analysis.....	68
2.3. Discussion of current gaps and challenges and relationship with thesis research directions	77
2.4. Summary and conclusions	89
3. RPAS REGULATIONS SURVEY	93
3.1. Introduction	94
3.1.1. Survey scope	97
3.1.2. Contents overview and structure	98
3.2. RPAS initial airworthiness and operations regulatory paradigm highlights	100
3.3. Previous reviews of RPAS regulations and research gap	103
3.4. Criteria and procedure employed in the survey	105
3.4.1. Definition of characteristics for the review of design-related airworthiness regulations.....	106
3.4.2. RPAS Regulatory Document Search Process	111

3.5. Survey of RPAS regulations on initial airworthiness and operational restrictions	112
3.5.1. Stage 1: Broad Review of Current Regulatory Landscape	113
3.5.2. Stage 2: Design and Operational Applicability of Selected Documents	123
3.6. Summary and conclusions	127
4. REVIEW OF FIXED-WING AIRCRAFT COMPUTERISED DESIGN ENVIRONMENTS	131
4.1. Chapter introduction and overview	131
4.1.1. Chapter objectives and structure	135
4.2. Previous related review works	138
4.3. Scope and hypotheses of the computerised design environment review	140
4.4. Current trends and challenges in computerised design environments	142
4.4.1. Knowledge-Based Engineering (KBE) capabilities	143
4.4.2. Modularity, interoperability, and integration	151
4.4.3. Design in distributed and collaborative environments	165
4.4.4. Framework extensibility	169
4.4.5. Method flexibility and multi-fidelity capabilities	172
4.4.6. Unconventional configurations	176
4.4.7. Remotely Piloted Aircraft Systems (RPAS)	182
4.5. Analysis of key features of computerised design environments	185
4.5.1. Identification of key features in aeroplane computerised design environments	186
4.5.2. Trend analysis for state-of-the-art design environments	192
4.5.3. Summary of the situation of existing design environments with respect to current trends and challenges	214
4.6. Discussion and key features towards future RPA design environments	216
4.6.1. Current state of design environments towards addressing the main challenges of RPAS design	216
4.6.2. Key areas of work towards the development of future initial sizing RPA design environments	223
4.7. Summary and conclusions	228
5. SELECTED TOPICS OF ARTIFICIAL INTELLIGENCE RELATED TO RPA DESIGN	233
5.1. Introduction to AI concepts and safety implications in aviation	234
5.1.1. Definition of AI and classification of techniques	235
5.1.2. Potential uses of AI in aviation and relevance of safety assurance	252
5.1.3. Rationale and objectives of this chapter in the context of the thesis	255
5.2. AI safety and regulations in aviation and link with RPA	259
5.2.1. Overview of current outputs from main aviation entities in matter of AI	260
5.2.2. Current research on AI safety characteristics and methodologies	264
5.2.3. Envisioned rulemaking concepts and organisation	267
5.2.4. Potential connections between AI areas of application and RPA regulations	269
5.3. Prospective applications of ontologies in aeroplane and RPA computerised design environments	275
5.3.1. Outline of current research on aircraft and RPA design using AI	277
5.3.2. Ontologies: background, modelisation and applications	280
5.3.3. Selection of symbolic AI and ontologies for their integration in aeroplane and RPA conceptual design	293
5.3.4. Review of current ontologies in areas related to manned aircraft and RPA design	300
5.3.5. Opportunities and challenges of ontology applications in aeroplane computerised design environments	310

5.4. Summary and conclusions	328
6. OVERVIEW OF RPA CONCEPTUAL DESIGN METHODOLOGIES DEVELOPED IN THIS THESIS	333
6.1. Motivation for the development of novel RPA conceptual design methodologies	334
6.1.1. Compilation of current gaps in RPA conceptual design	334
6.1.2. Gap summary and interdependency analysis	337
6.1.3. Approach of the thesis towards addressing RPA conceptual design gaps.....	342
6.2. Suite of RPA conceptual design methods: development approach and structure	344
7. STATISTICAL APPROACHES FOR RPA CONCEPTUAL DESIGN	349
7.1. Chapter introduction, overview and structure	350
7.2. State-of-the-art of statistical approaches in RPA design.....	354
7.3. Overview of fundamental statistical concepts	360
7.3.1. Corrected and standardised variables	361
7.3.2. Covariance and correlation matrices	362
7.3.3. Hypothesis testing	363
7.4. Materials and methods	366
7.4.1. Regression analysis.....	366
7.4.2. Factor analysis.....	375
7.4.3. RPA database	388
7.5. Challenges in RPA statistical analysis	400
7.6. Regression analysis results and design methodology	404
7.6.1. Sub-dataset selection	405
7.6.2. Regression results and histograms for specific design variables.....	407
7.6.3. Geometry sizing process for conceptual design	418
7.6.4. Correlation analysis method case studies	421
7.7. Factor analysis results and design methodology	424
7.7.1. Calculations, results and discussion.....	425
7.7.2. Conceptual design method for H-Tail RPA based on factor analysis	447
7.7.3. Factor analysis method case study	450
7.8. Summary and conclusions	453
8. AIRWORTHINESS BASED APPROACHES FOR RPA CONCEPTUAL DESIGN.....	457
8.1. Chapter introduction, overview and structure	457
8.2. Integration of airworthiness requirements in design approaches	461
8.3. Previous works in design and airworthiness integration	467
8.4. Flexible procedure for Design Criteria Extraction (DECEX).....	473
8.4.1. Rationale for the Development of the DECEX Procedure	473
8.4.2. DECEX Application Workflow	477
8.5. Example Application Cases	479

8.5.1. Case Study 1: Tactical RPA.....	480
8.5.2. Study 2: HALE RPA	483
8.6. Summary and conclusions	486
9. MULTI-ROLE RPA CONCEPTUAL DESIGN APPROACH BASED ON INTEGRAL PERFORMANCE	489
9.1. Chapter introduction, overview and structure	490
9.1.1. Objectives and scope of the models.....	496
9.1.2. Contents overview and chapter structure	498
9.2. Research background and state-of-the-art analysis	500
9.2.1. Mission flight profiles	502
9.2.2. Drag polar models and estimation methods.....	505
9.2.3. Propeller analysis models	508
9.2.4. Flight laws, integral performance equations and PL-R/PL-E diagrams	511
9.2.5. Overview of previous research on RPA performance estimation methods.....	516
9.2.6. Outline of previous research on mission-based aircraft design	518
9.2.7. Summary of gaps towards RPA mission analysis and synthesis methods	521
9.3. Development of novel RPA performance and design models.....	522
9.3.1. Rapid performance estimation method for multi-mission RPA.....	523
9.3.2. Initial sizing approach for multi-Role RPA	540
9.4. Performance estimation results and discussion: flight law analysis	553
9.4.1. Constant airspeed flight law	554
9.4.2. Constant lift coefficient flight law.....	563
9.5. Performance estimation results and discussion: sensitivity analyses	568
9.6. Multi-role initial sizing results and discussion	574
9.6.1. Validation case: Seeker 2E.....	574
9.6.2. Application case.....	577
9.7. Summary and conclusions	582
10. OVERALL CONCEPTUAL DESIGN METHOD RESULTS AND DISCUSSION.....	585
10.1. Considerations for the combined use of the design approaches	585
10.1.1. Combination of multi-role performance and statistical sizing approaches.....	588
10.1.2. Integration of airworthiness considerations in multi-role initial sizing approach	588
10.1.3. Configuration selection approach.....	591
10.2. Application case to initial sizing of small RPA.....	592
10.2.1. Design case description and specifications	593
10.2.2. Initial sizing and comparison between configurations	594
10.3. Conclusions	597
11. DISCUSSION	599
11.1. Specific discussion points related to each of the topics covered in the thesis.....	599
11.2. Overall discussion of topic connections and common considerations	603

12. CONCLUSIONS AND FUTURE RESEARCH.....	607
12.1. Conclusions on specific topics of the research.....	607
12.1.1. Statistical methodologies for RPA conceptual design	607
12.1.2. RPAS regulations and airworthiness-based design approaches.....	609
12.1.3. Multi-role RPA integral performance analysis and design	611
12.2. Future work: integration of RPA design approaches in computerised environment enhanced by ontologies	612
12.3. Overall concluding remarks	618
References	621

List of Figures

Figure 1-1. Schema representing the different phases of the design process and their context, as well as the scope focus of this thesis.	4
Figure 1-2. The figure above represents the worldwide civil RPAS production value by purpose of application, obtained from (26). The figure below showcases the estimated registration of large RPAS within the Part-47 registry in the USA, obtained from (27).	10
Figure 1-3. Various examples of fixed-wing RPAS, showcasing the variety in layouts and powerplants, among other aspects. (a) RQ-11 Raven, with conventional tail, single boom and electric powerplant, (b) Aerosonde, with inverted V-tail, double tail booms and piston engine, (c) Nostromo Yarara, with T-tail, single tail boom and piston engine, (d) ScanEagle, with tailless configuration and piston engine, (e) Pioneer, with H-tail, double booms and piston engine, (f) Heron 1, with H-tail, double booms and piston engine, (g) Reaper, with Y-tail and turboprop engine, (h) Tapas II, with T-tail and twin piston engines, and (i) Global Hawk, with V-tail and turbofan engine. All images obtained from commons.wikimedia.org.	13
Figure 1-4. Order and connections among the different objectives of the doctoral research, along with an advance of the main associated gaps and findings.	25
Figure 1-5. Organisation schema of the contents of the thesis.	29
Figure 2-1. Illustration of the concepts of analysis and synthesis approaches.	36
Figure 2-2. Comparison of the rationale, development process and characteristics of Generic Design Methods (GDM) and Ad-Hoc Developed Design Methods (ADDM), following the definitions from the main text.	50
Figure 2-3. Notional concept of a computerised design environment, in this case developed for the conceptual design stage.	55
Figure 2-4. Conceptual representations of topics used in the survey, the connections among them, and the typical design phase in which they are employed. Note that horizontal positioning does not represent the order of use in the design continuum.....	67
Figure 2-5. Summary of connections of findings of the overall RPA design survey with other chapters and parts of the thesis.	86
Figure 2-6. Organisation of the contents and chapters of the thesis attending to both the research flow and the level of granularity of the topics at each step. The connections and influences of the broader topics on the more specific ones, and vice-versa, are also shown.	88

Figure 3-1. Summary of main regulatory highlights in the areas of initial airworthiness and operational categories from civil organisations with marked international influence. EU (European Union), JARUS (Joint Authorities for Rulemaking on Unmanned Systems), A-NPA (Advanced Notice of Proposed Amendment), sUAS (small Unmanned Aircraft Systems), CS (Certification Specifications), LURS (Light Unmanned Rotorcraft Systems), CONOPS (Concept of Operations), NPRM (Notice of Proposed Rulemaking), SC (Special Condition), LUAS (Light Unmanned Aeroplane Systems), IR (Implementing Regulation), DR (Delegated Regulation), SORA (Specific Operations Risk Assessment), USC (United States Code), AC (Advisory Circular), HAPS (Hight Altitude Platform Systems (HAPS)). 96

Figure 3-2. Outline of the main sections of the present chapter, detailing the connections among them, and also the elements that will be directly employed in the research conducted within chapter 8 of the thesis..... 99

Figure 3-3. Representations of the organisation and interrelations amongst CS codes within the future EASA RPAS framework. Figure adapted from (162). 115

Figure 4-1. Schema of the contents of the chapter, showcasing their relationships with the three main objectives and presented along with overall considerations for the review and discussion. 137

Figure 4-2. Example comparison between data schemas of two data formats employed in computerised environments. (a) CPACS, retrieved from (186), (b) ADML, retrieved from (240). 148

Figure 4-3. Example of flexibility at the discipline model level, corresponding to the GENUS environment. The upper image corresponds to the generic case, and the lower one to the BWB design, where mass estimation and stability modules have been swapped. Images obtained from (50). 155

Figure 4-4. Example of flexibility at the workflow level, corresponding to the AGILE environment. The workflow presented here corresponds to a truss-braced wing aircraft. This image is complemented with the one below to showcase the change in the workflow. Images obtained from (155). 156

Figure 4-5. Example of flexibility at the workflow level, corresponding to the AGILE environment. The workflow presented here corresponds to a BWB, with the overall structure of the workflow being different than that of the preceding figure. Images obtained from (155). 157

Figure 4-6: comparison between interface evolution depending in the number of modules. (a) for 4 modules, 12 interfaces when following a decentralised approach, equation [4-1], (b) 8

interfaces when following a centralised approach, equation [4-2], (c) the gain in interface efficiency is more remarkable when the number of modules in the environment increases.

.....164

Figure 4-8: examples of revolutionary unconventional aeroplane configurations. (a) Left-hand-side image: box wing configuration example from Lockheed Martin (image from commons.wikimedia.org). (b) Right-hand-side image: BWB configuration from Boeing-NASA (image from commons.wikimedia.org). 179

Figure 4-9. Relationships among the different trends analysed in section 4.4, represented by the boxes, along with the selected features which are related to the design environment performance for each of them, represented by the text below the boxes. Each trend has been associated to the two main areas of interest in the overall realm of computerised environments as laid out in section 4.1.....188

Figure 4-10. Number of overall environments including analysis and design capabilities for manned or unmanned aeroplanes, including those which cover both types.....193

Figure 4-11. Phases of the design process covered by each design package functionality area when separating by manned and unmanned design aspects.....195

Figure 4-12. Number of overall design environments which can conduct analysis and design tasks for each aircraft type. For the “unmanned undefined” category, the authors of the package have stated that it can size RPA, but no further details on size or mass range have been given. 197

Figure 4-13. Number of design environments with capabilities related to different general layouts of the aerodynamic surfaces, either with demonstrated disciplinary analysis or geometric representation.....200

Figure 4-14. Number of design package functionality areas compatible with the modelisation of different powerplant types. The horizontal lines represent, following the same criteria as the bar legend, the overall number of design package functionality areas for manned and unmanned aircraft. 202

Figure 4-15. Number of design environments/functionality areas presenting each of the general design software capabilities. (a) Showcases the number of functionality areas which present the different capabilities save for method flexibility and multi-fidelity. The horizontal lines represent, following the same criteria as the bar legend, the overall number of design package functionality areas for manned and unmanned aircraft. (b) Illustrates the number of packages grouped by aircraft type showcasing method flexibility and multi-fidelity capabilities. 204

Figure 4-16. Number of design environment functionality areas presenting each of different disciplinary modules. The vertical lines represent the overall number of design package functionality areas for manned (continuous line) and unmanned (dashed line) aircraft. (a) covers the modules for the functionality area of manned aircraft, and (b) does the same for the area of unmanned aircraft.	209
Figure 5-1. Conceptual map of the intelligent agent, its main dimensions, and their relationship with knowledge representation elements.	238
Figure 5-2. High-level comparison between main features of the two main branches of AI considered within this thesis. The characteristics are developed in detail within the text...	240
Figure 5-3. Conceptual schema illustrating the relationship of the two main lines of research of chapter 5 with the areas of interest of AI within the aviation domain and with the topics studied in previous thesis chapters.	259
Figure 5-4. EASA schema of trustworthiness evaluation of AI system, based on four interconnected building blocks. Retrieved from EASA AI Roadmap v2 (55) and Concept Paper v2 (238).	262
Figure 5-5. EASA concept for AI rulemaking organisation, with a transversal Part-AI and also domain-specific integration of AI aspects in other regulations. Obtained from EASA AI Roadmap v2 (55).	268
Figure 5-6. Prospective connections among different areas of AI application, as identified in the EASA AI Roadmap, and current standards and rulemaking areas for RPA regarding design, operations, and U-space. SERA (Standardised European Rules of the Air), ACAS (Airborne Collision Avoidance System), MEDUSA (Methodology for the U-space Safety Assessment).	271
Figure 5-7. Contextualisation of ontologies within the areas of KE and AI, building on the generic schema provided beforehand in Figure 5-1.	282
Figure 5-8. Ontology and data example, linking two classes (Aircraft and Component) through a property which represents the relation between them (hasComponent), the attribute name for the aircraft and the hierarchy of components (Engine as a subconcept of Component), and the use of the ontology in the data linking a particular aircraft to its engine and its name.	284
Figure 5-9. Ontology expressivity continuum from lightweight to heavyweight ones. Reproduced from (265).	285

Figure 5-10. References relative to ontologies for aeroplane design located within different related topical areas. RPAS have been considered as a particular scenario of aircraft design, accounting for the fact that the scope of this investigation is set on fixed-wing RPAS.....	309
Figure 6-1. Conceptual schema of topical areas of RPA covered in the thesis, their relationships and the contributions of each part of the thesis related to the topics.....	345
Figure 7-1. Workflow of chapter 7 and connection with other lines of research of the thesis.	354
Figure 7-2. Two-tailed hypothesis testing corresponding to a normal distribution Image retrieved from: https://online.stat.psu.edu/statprogram/book/export/html/524	365
Figure 7-3. For a fixed sample size of $n=10$, the evolution of the corrected R^2 value is calculated for different numbers of predictor variables and for distinct values of the original R^2	373
Figure 7-4. Factor analysis mathematical procedure roadmap. The steps of the process which are affected by particularities of aircraft conceptual design have been indicated. The meanings of the different variables and indexes shall be expounded further below in the main text.	376
Figure 7-5. Summary of the factor analysis exposition. z_j represents the observable variables, in corrected and standardised format. Attending to the orientation of the arrows, the z variables are determined by both the common unobservable factors f_k , of which there are q in total, and by the corresponding specific factor e_j unique to each observable variable. ...	377
Figure 7-6. Factor analysis application roadmap to the RPA database. The results obtained shall be employed and tested for the sizing of new RPA not included in this database.	387
Figure 7-7. Histograms quantifying the number of aircraft in the database according to the general configuration and tail union with airframe classifications.....	392
Figure 7-8. Number of RPA in the aircraft as classified by powerplant type.	393
Figure 7-9. Use of different powerplant types along the continuum of MTOM values for the full database.	394
Figure 7-10. Analysis of interactions among general configuration, tail union type, and MTOM.	395
Figure 7-11. Analysis of interactions among wing planform type, general configuration, and MTOM.....	396
Figure 7-12. Use of different propeller pitch types along the continuum of MTOM values for the full database.....	397

Figure 7-13. Illustration of the ways in which the lack of data cells impacts the resulting data matrix depending on the type of statistical approach: multivariate or bivariate.....	403
Figure 7-14. S_w – MTOM regression for all sub-dataset layouts. $R^2 = 0.961$, RMSE = 0.8465.	409
Figure 7-15. Span loading – MTOM regression for all sub-dataset layouts, with high Aspect Ratio ($AR \geq 11$) for the golden curve, with $R^2 = 0.969$ and RMSE = 3.54, and low Aspect Ratio ($AR < 11$) for the silver curve, with $R^2 = 0.979$ and RMSE = 4.34.	410
Figure 7-16. Histogram for the equivalent wing taper ratio attending to the original wing planform area. All rectangular wings and straight-tapered ones have a direct correspondence to the original wing, with the rectangular ones all showing a unit value of taper ratio.....	411
Figure 7-17. S_h – S_w regression for conventional tail, T-tail and H-tail layouts.. $R^2 = 0.975$, RMSE = 0.100.....	411
Figure 7-18. Histogram for the horizontal tail volume coefficient attending to the tail type. The values proposed in previous works have been represented as vertical lines.....	412
Figure 7-19. L_h – L_v regression for conventional tail, T-tail and H-tail layouts, with the top curve corresponding to low HTP positions, with $R^2 = 0.997$ and RMSE = 0.080, and the bottom curve corresponding to intermediate or high HTP positions, with $R^2 = 0.978$ and RMSE = 0.080.	413
Figure 7-20. Histogram for the vertical tail volume coefficient attending to the tail type. The values proposed in previous works have been represented as vertical lines.....	414
Figure 7-21. S_{vee} – S_w regression for V-tail layouts. $R^2 = 0.973$, RMSE = 0.324.	414
Figure 7-22. Regression related to the V-tail volume coefficient, with the predictor variable representing its denominator and the response variable its numerator. $R^2 = 0.964$, RMSE = 1.26.....	415
Figure 7-23. I_f – L_{vtail} regression attending to the tail union with the fuselage, with the top curve corresponding to a direct union, with $R^2 = 0.961$ and RMSE = 0.645, and the bottom curve corresponding to a tail boom union, with $R^2 = 0.836$ and RMSE = 0.446.	416
Figure 7-24. I – L_{tail} correlation for all layouts in the sub-dataset. $R^2 = 0.952$, RMSE = 0.439.	417
Figure 7-25. The left-hand-side figure is the histogram for the fuselage slenderness attending to the tail union type. The right-hand-side figure shows the histogram for tail boom slenderness, in which the two main types of tail boom configurations have been differentiated.	417

Figure 7-26. Geometric sizing workflow based on the application of the statistical results obtained through the regression analysis.	420
Figure 7-27. Depiction of the cruise speed (V_c) versus the Maximum Take-Off Mass (MTOM) for all RPA with reciprocating engine and H-tail.....	429
Figure 7-28. Representation of the population R^2 versus the number of variables considered in the factor analysis study v and the original R^2 for a sample size n of 53 RPA.	431
Figure 7-29. Scree plot for the factor extraction of the global design variables case study. The x-axis represents the number of the eigenvalue corresponding to each of the possible common factors when sorted in descending order of the associated score, with this latter value being represented in the y-axis.	432
Figure 7-30. For the global design variable case, the graph above represents the variance accounted for by the common factor which is shared amongst all variables (communality) and the variance related to the specific factor particular to each of them (uniqueness). The graph below shows the percentage difference in absolute value between the application of the PF and Minres methods for factor extraction, calculated for each common factor loading.	435
Figure 7-31. Multiple linear regression coefficients of the correlation to estimate the RPA scale common factor f_s as a function of the observable variables for the global design variables application case.	436
Figure 7-32. Linear regression Scale Factor – MTOM for the $n = 53$ RPA remaining in the data matrix of this application case. $R^2 = 0.989$, $RMSE = 0.1072$	437
Figure 7-33. Representation of the population R^2 versus the number of variables considered in the factor analysis study v and the original R^2 for a sample size n of 18 RPA.	438
Figure 7-34. For the aerodynamic surface design variable case, the graph above represents the variance accounted for by the common factor which is shared amongst all variables (communality) and the variance related to the specific factor particular to each of them (uniqueness). The graph below shows the percentage difference in absolute value between the application of the PF and Minres methods for factor extraction, calculated for each common factor loading.	443
Figure 7-35. Multiple linear regression coefficients of the correlation to estimate the RPA aerodynamic surface factor f_a as a function of the observable variables for the aerodynamic surface design variables application case.	444

Figure 7-36. Multiple linear regression of Aerodynamic Surface Factor – [MTOM, S_w] for the $n = 18$ RPA remaining in the data matrix of this application case. $R^2 = 0.9915$, RMSE = 0.0929.	446
Figure 7-37. Comparison between the errors in the estimation of the different variables for the RQ-2 Pioneer RPA employing both approaches developed in this chapter of the thesis. The variable P_E was not available in the regression method.	452
Figure 8-1: Conceptual representation of difference in breadth and certification assurance of constrained design spaces according to requirements of differing levels of specificity. Some candidate designs may be left out in the case of a higher specificity level but, as a trade-off, the assurance in certifiability can be expected to be higher.	466
Figure 8-2: DECEX procedure workflow. This schema has assumed that a GDM approach is being populated with airworthiness requirements; however, it can also be applied directly to a design process, accounting for its scope in step 1. The numbers indicate the main workflow highlights and are commented in the main text.....	476
Figure 8-3. Matching diagram for the first case study, considering the restrictions mentioned in the main text. Constraints mainly related with performance initial specifications are in blue, and those related to certification aspects are in green. The arrows indicate where the feasible design region lies for each of the constraints. The feasible design regions with and without considering certification constraints are identified.	483
Figure 8-4. Matching diagram for the second case study, considering the restrictions mentioned in the main text. Constraints mainly related with performance initial specifications are in blue, and those related to certification aspects are in green. The arrows indicate where the feasible design region lies for each of the constraints. The feasible design regions with and without considering certification constraints are identified.....	485
Figure 9-1. Conceptual representation of the difference between a single-role and multi-role aircraft, both with a similar set of off-design missions defined through the PL-R envelope, but with distinct design missions which have been used to size the aircraft.....	494
Figure 9-2. Conceptual map of the different models, as well as their connections, involved in the creation of the analysis and synthesis approaches based on integral performances developed within this chapter. The chart contains the sections where each step is expounded, as well as the connection with the statistical models developed in chapter 7.	499
Figure 9-3. Representation of two notional flight profiles representative of distinct types of missions. The red arrows represent the “fuel intensive phases”, which are those in which the majority of the fuel is consumed, and thus the focus of integral performance methods.	503

Figure 9-4: notional Payload-Range (PL-R) diagram, with the design mass corresponding to each restriction indicated.	511
Figure 9-5. Simplified schema illustrating the main underlying idea and purposes behind the proposed performance analysis methodology. Φ represents the flight law, which in this case can either be defined by a constant speed or lift coefficient. The meanings of the remaining variables have been given previously along the text.	523
Figure 9-6: representation of TOM and FM iso-curves and their relationship with the limitations of the PL-R diagram.....	526
Figure 9-7. Proposed mission profile to be used in the performance analysis methodology, comprising three fuel intensive segments and allowing parametric variations. Symbols in bold indicate values which can be directly modified by the designer. The values of m_i represent the mass of the aircraft at each of the segment begin and end points. The definition of other variables is given in the main text.....	529
Figure 9-8. Computation diagram of the performance model for the mission stage. Symbols are defined in the main text and in Table 9-1.	534
Figure 9-9. Schematic representation of the proposed design loop for integral performance-based conceptual design, with three main steps.	543
Figure 9-10. Approaches for integral performance-based mass estimation. (A) represents a traditional single-mission approach, as followed in many classical references. (B) illustrates the procedure to be followed within this thesis. The continuous lines represent the final closing envelope of the diagram, which are selected in the multi-role approach as the combination of cases so that every mission point is covered, while avoiding an oversized diagram.	545
Figure 9-11. Multiple linear regression of OEM – [MPL,MFM] for conventional tail, T-tail, V-tail, and H-tail RPA with reciprocating engines. $R^2 = 0.9461$, RMSE = 68.26.	548
Figure 9-12. Workflow of the mass estimation step of the proposed multi-role RPA design methodology.	549
Figure 9-13. The left-hand-side image represents the PL-R and PL-E diagrams for the RQ-2 Pioneer under the conditions of zero α and R_{ineg} . The right-hand-side image corresponds to the diagram but in this case using the case study data.....	555
Figure 9-14. Variation of PL-R and PL-E envelopes for different flight speeds for the RQ-2 Pioneer RPA case study.	556
Figure 9-15. Iso-curves for average C_L value along the mission stage and for the difference between the maximum and minimum C_L value also along each flight, represented for different	

flight speeds corresponding to the RQ-2 Pioneer RPA case study. The approximate region representing missions where stall happens at some point along the flight has been highlighted in red.....	558
Figure 9-16. Iso-curves for TF and FW for the Pioneer at two different flight speeds.....	559
Figure 9-17: Iso-curves for TOW and LW for the Pioneer at two different flight speeds.....	560
Figure 9-18. Iso-curves for both average Ω_E value and its delta along the mission stage, for different flight speeds corresponding to the RQ-2 Pioneer RPA case study.....	561
Figure 9-19. Iso-curves for maximum Ω_E and M_{ptip} along the mission stage, represented for different flight speeds corresponding to the RQ-2 Pioneer RPA case study. The region where noise issues might appear due to the propeller angular velocity is highlighted in orange, and that where transonic effects occur is marked in red.....	562
Figure 9-20. Variation of PL-R and PL-E envelopes for different lift coefficients for the RQ-2 Pioneer RPA case study.....	564
Figure 9-21. Iso-curves for both average V value along the mission stage and its delta for different flight C_L values corresponding to the RQ-2 Pioneer RPA case study.....	565
Figure 9-22. Iso-curves for TF and FW for the Pioneer at two different lift coefficient values.	566
Figure 9-23. Iso-curves for maximum Ω_E and M_{ptip} along the mission stage, represented for different lift coefficients corresponding to the RQ-2 Pioneer RPA case study. The region where noise issues might appear due to the propeller angular velocity is highlighted in orange, and that where transonic effects occur is marked in red.....	567
Figure 9-24. Sensitivity analysis of the PL-R and PL-E envelopes of the RQ-2 Pioneer upon changing the reserve fuel percentage.	570
Figure 9-25. Sensitivity analysis of the PL-R and PL-E envelopes of the RQ-2 Pioneer upon changing the OEW.	571
Figure 9-26. Sensitivity analysis of the PL-R and PL-E envelopes of the RQ-2 Pioneer upon changing the value of C_{D0}	572
Figure 9-27. Sensitivity analysis of the PL-R and PL-E envelopes of the RQ-2 Pioneer upon changing the value of the drag polar coefficient $k \equiv C_{D2}$	573
Figure 10-1. Wing loading variation with MTOM for as determined by the statistical approaches.....	589

Figure 11-1. Summary of model adaptations when considering the challenges and peculiarities of RPA.	606
Figure 12-1. Connections among the needs assessment areas, the main contributions of the thesis, and future lines of research.	614
Figure 12-2. Example schema of the proposed computerised design environment for Remotely Piloted Aircraft (RPA). The numbers identify the different areas where ontologies would be incorporated. Heron 1 aircraft image from: commons.wikimedia.org	615

List of Tables

Table 2-1. Summary of main characteristics of the three aircraft design phases. Information has been mainly obtained from (11), with some modifications.	38
Table 2-2. Compilation of previous research works focused on the investigation of specific design approaches for RPA, classified within the different topical areas considered in the survey.	69
Table 3-1. State-of-the-art overview of surveys and analyses on RPAS regulations, and comparison with the survey conducted in this chapter.	104
Table 3-2. Examples of the level of specificity concept applied to three different requirements within the field of RPAS.	110
Table 3-3. Summary of findings from the first stage of the survey. The table footer contains the meaning of the different symbols employed.	120
Table 3-4. Summary of findings from the second stage of the survey. The table footer contains the meaning of the different symbols employed.	125
Table 5-1. Summary of contrasting aspects between symbolic and subsymbolic AI approaches.	250
Table 5-2. Summary of references covering the topic of ontology engineering for aeroplane design and related areas, organized by aeronautical field of application, including those related specifically to RPA design, and also sorted by each of the previously identified ontology fields of application. The citations are accompanied, where applicable, with the given names of the ontologies developed in the research or related to it.	307
Table 5-3. Matching of computerised design environments main trends and challenges with the main strengths and areas of application of ontologies. Please note that the rows correspond to the challenges of design packages as analysed in section 4.4, and the columns to the fields of application of ontologies as seen in subsection 5.3.4. The content of each cell reflects a possible area of ontology applications, each of which shall be discussed in the main text, organized by their numbering as presented here. Where references are cited, they correspond to works that have investigated the related applications before.	312
Table 7-1. Summary of previous statistical analysis works on the domain of RPA vehicle design. When a classification has been employed to group RPAS to extract different trends for each of these categories, this has been highlighted.	356

Table 7-2. Summary of the main classification criteria and categories considered in this research.	391
Table 7-3. Example variables of the database which have an influence in later statistical analyses, along with the percentage of aircraft of the database for which the variable's value is known. "Data" indicates that the value is found directly as numerical information within the data sources consulted to compile the database. "Measured" designates those cases where measurements on three-view drawings were obtained to complement the scarce volume of data directly found on the references.	398
Table 7-4. Case study of the geometry sizing process based on regressions for the XPV-1 Tern.	422
Table 7-5. Case study of the geometry sizing process based on regressions for the RQ-2 Pioneer.	422
Table 7-6. Case study of the geometry sizing process based on regressions for the Hermes 450.	423
Table 7-7. Correlation matrix for the global design variables.	428
Table 7-8. Population inference statistical parameters for the communality estimation within the study of global design variables.	430
Table 7-9. Coefficients of the factor pattern matrix associated with the extraction of one factor for the global design variables application case, accompanied by their corresponding p-values analysed as Pearson linear correlation coefficients. Results are shown for both the PF and Minres methods. The cutoff value for the coefficient for a sample size of $n = 53$ is of $r = 0.271$ in order to guarantee statistical significance with a 0.05 level of significance, which corresponds to the p-value limit for a F-Fisher one-sided test.	433
Table 7-10. Correlation matrix for the aerodynamic surface design variables.	439
Table 7-11. Population inference statistical parameters for the study of aerodynamic surface design variables.	440
Table 7-12. Coefficients of the factor pattern matrix associated with the extraction of one factor for the aerodynamic surface design variables application case, accompanied by their corresponding p-values analysed as Pearson linear correlation coefficients. Results are shown for both the PF and Minres methods. The cutoff value for the coefficient for a sample size of $n = 18$ is of $r = 0.4683$ in order to guarantee statistical significance.	442
Table 7-13. Case study of the geometry sizing process based on factor analysis for the RQ-2 Pioneer.	451

Table 8-1. Summary of obstacles towards airworthiness-design integration in the field of RPA methodologies, as extracted from the findings, discussions, and conclusions within chapter 3.	459
Table 8-2. Overview of main characteristics of selected works within the state-of-the-art pertaining to airworthiness and design aspects, with a main focus on the integration of airworthiness aspects within aircraft design activities. The column “Design Stage Focus” evaluates references attending to the aircraft design stage taxonomy used through this thesis. References are organised attending to citation order within the main text.	469
Table 8-3: Results summary of DECEX procedure application for the first case study, focused on a tactical RPA.....	481
Table 8-4. Results summary of DECEX procedure application for the second case study, focused on a HALE RPA.....	484
Table 9-1: symbols and interpretation employed in the computational procedure for performance resolution at the mission stage.....	535
Table 9-2. Summary of IFs considered in the drag polar model, based on (9; 47).....	551
Table 9-3. Data of the RQ-2 Pioneer to be employed in the performance estimation case study. Aircraft information obtained from (366; 367; 368).	553
Table 9-4. Summary of inputs for the multi-role design methodology applied to the case study corresponding to the Seeker 2E. Information mainly obtained from (33; 312; 366).	575
Table 9-5: results from the Seeker 2E validation case.	576
Table 9-6. Summary of inputs for the multi-role design methodology conducted for the RPA application case considering three design missions.....	578
Table 9-7: results from the application case of the multi-role methodology. The number combinations represent the joint missions that have been considered in each design case.	579
Table 10-1: Results summary of DECEX procedure application for the small RPA case study	594
Table 10-2. Summary of requirements for the small RPA multi-role design case.....	594
Table 10-3. Results from the small RPA sizing case of the multi-role sizing methodology....	595

Abbreviations and acronyms

AAA	Advanced Aircraft Analysis
AADM	Ad hoc Developed Design Methods
AC	Advisory Circular
ACARE	Aviation Research and Innovation in Europe
ACAS	Airborne Collision Avoidance System
ACAS Xu	Airborne Collision Avoidance System for unmanned aircraft
ADAPT	Aircraft Design, Analysis, Performance and Tradespace
ADDAM	Aircraft Design DATA Model
ADEBO	Aircraft DESIGN BOX
ADS	Airworthiness Design Standards
ADS	Automated Design Synthesis
ADML	Aircraft Design Markup Language for Multidisciplinary Aircraft Design and Analysis
AEP	Allied Engineering Publication
AGL	Above Ground Level
AI	Artificial Intelligence
AIDA	Artificial Intelligence supported conceptual Design of Aircraft
AMC	Acceptable Means of Compliance
ANN	Artificial Neural Network
ANOVA	Analysis Of Variance
A-NPA	Advanced Notice of Proposed Amendment
ANSI	American National Standards Institute
APD	Aircraft Preliminary Design
AR	Aspect Ratio
ASTM	American Society for Testing and Materials

ATA	Air Transportation Association
ATC	Air Traffic Control
ATM	Air Traffic Management
AV	Autonomous Aerial Vehicle
AVL	Athena Vortex Lattice
BARS	Basic Aviation Risk Standard
BWB	Blended Wing Body
CAA	Civil Aviation Authority
CAD	Computer Aided Design
CATIA	Computer-Aided Three-dimensional Interactive Application
CBO	Community- Based Organization
CBR	Case-Based Reasoning
CCADE	Collaborative Conceptual Aircraft Design Environment
CEASIOM	Computerised Environment for Aircraft Synthesis and Integrated Optimisation Methods
CeRAS	Central Reference Aircraft data System
CFD	Computational Fluid Dynamics
CG	Centre of Gravity
COA	Certificate of Authorization
CoDANN	Concepts of Design Assurance for Neural Networks
CONOPS	Concept of Operations
CPACS	Common Parametric Aircraft Configuration Scheme
CS	Certification Specification
CREATE-AV	Computational Research and Engineering Acquisition Tools and Environments – Air Vehicles
DAA	Detect and Avoid
DARPA	Defense Advanced Research Projects Agency

DAVE-ML	Dynamic Aerospace Vehicle Exchange Markup Language
DECEX	Design Criteria Extraction
DECODE	Decision Environment for COmplex DEsigns
DOF	Degrees of Freedom
DesO	Design Ontology
DGM	Deep Generative Models
DLR	Deutsches Zentrum für Luft-und-Raumfahrt
DNN	Deep Neural Networks
DocO	Documentation Ontology
DoD	Department of Defense (USA)
DR	Delegated Regulation
DTT	Distance To Target
EASA	European Union Aviation Safety Agency
EC	European Commission
EDA	European Defence Agency
EU	European Union
EUROCAE	European Organisation for Civil Aviation Equipment
EUROCONTROL	European Organisation for the Safety of Air Navigation
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulations
FAST	Fixed-wing Aircraft Sizing Tool
FEA	Finite Element Analysis
FEM	Finite Element Method
FLOPS	Flight Optimization System
FM	Fuel Mass
FMECA	Failure Mode, Effects and Criticality Analysis
FTA	Fault Tree Analysis

FW	Fuel Weight
GCS	Ground Control Station
GDM	Generic Design Methods
GenAI	Generative AI
GM	Guidance Material
GPT	Generative Pre-trained Transformer
GR	Gear Ratio
HALE	High-Altitude Long Endurance
HAPS	Hight Altitude Platform Systems
HTOL	Horizontal Take-Off and Landing
HTP	Horizontal Tail-Plane
IAI	Israel Aerospace Industries
ICAO	International Civil Aviation Organization
ICARUS	Information Catalyst for Aviation Services
IoT	Internet of Things
IR	Implementing Rules
ISA	International Standard Atmosphere
ISO	International Organization for Standardization
ISR	Intelligence, Surveillance and Reconnaissance
JAA	Joint Aviaron Authorities
JARUS	Joint Authorities for Rulemaking on Unmanned Systems
KAS	Korean Airworthiness Standard
KB	Knowledge-Based
KBE	Knowledge-based Engineering
KBS	Knowledge Based Systems
KE	Knowledge Engineering
KEACDE	Knowledge-Based and Extensible Aircraft Conceptual Design Environment

LALE	Low Altitude Long Endurance
LEAPS	Layered and Extensible Aircraft Performance System
LES	Large Eddy Simulations
LG	Landing Gear
LLM	Large Language Model
LM	Landing Mass
LOC	Loss of Control
LOS	Line of Sight
LOT	Linked Open Terms
LRD Tier	Level of Regulatory Document Tier
LUAS	Light Unmanned Aircraft System
LUC	Light UAS Operator Certificate
LURS	Light Unmanned Rotorcraft System
MAC	Mean Aerodynamic Chord
MALE	Medium-Altitude Long Endurance
MAV	Micro Aerial Vehicle
MDO	Multidisciplinary Design Optimization
MEDUSA	Methodology for the U-space Safety Assessment
MFM	Maximum Fuel Mass
MGC	Mean Geometric Chord
ML	Machine Learning
MLEAP	Machine Learning Application Approval
MoD	Ministry of Defence (UK)
ModO	Model Ontology
MPL	Maximum Payload
MS	Member State
MS	Mean Square
MSE	Mean Squares Error

MSR	Mean Square Regression
MTOM	Maximum Take-Off Mass
MTOW	Maximum Take-Off Weight
NAA	National Aviation Authority
NASA	National Aeronautics and Space Administration
NASTRAN	NASA Structural Analysis System
NATO	North Atlantic Treaty Organization
NAV	Nano Air Vehicles
NeOn	Networked Ontologies
NLP	Natural Language Processing
NPA	Notices of Proposed Amendment
NPRM	Notice of Proposed Rulemaking
NRL	Naval Research Laboratory
OAV	Organic Aerial Vehicle
OBJ	objective
OEM	Operating Empty Mass
OEW	Operational Empty Weight
OML	Outer-Mold Line
OO	Object-Oriented
OOPS!	OntOlogy Pitfall Scanner!
OP	Overarching Property
OOP	Object-Oriented Programming
OSO	Ontology for Scenario Orchestration
OSO	Operational Safety Objective
OWL	Web Ontology Language
PF	Principal Factor
PL	Payload
PL-E	Payload-Endurance

PL-R	Payload-Range
RADE	Rapid Airframe Design Environment
RAMP	RPAS Advance MDO Platform
RANS	Reynolds Averaged Navier Stokes
RBR	Rule-Based Reasoning
RCE	Remote Component Environment
RCS	Radar Cross Section
RCT	research contributions of the thesis
RDB	Relational Data-Base
RDF	Resource Description Framework
RDFS	RDF Schema
RF	Reserve Fuel
RMSE	Root Mean Square Error
RPA	Remotely Piloted Aircraft
RPAS	Remotely Piloted Aircraft System
RPS	Remote Pilot Station
RPV	Remotely Piloted Vehicle
SAE	Society of Automobile Engineers
SAIL	Specific Assurance and Integrity Level
SAR	Search and Rescue
SARPs	Standards and Recommended Practices
SC	Special Condition
SERA	Standardised European Rules of the Air
SFC	Specific fuel consumption
SMR	Small and Medium Reconnaissance
SORA	Specific Operations Risk Assessment
SoS	System of Systems
SPARQL	SPARQL Protocol and RDF Query Language

SS	Sum of Squares
SSE	Sum of Squares Error
SSR	Sum of Squares Regression
SST	Sum of Squares Total
STANAG	Standardization Agreement
sUAS	small Unmanned Aircraft Systems
SUAVE	Stanford University Aerospace Vehicle Environment
TF	Trip Fuel
TLR	Technology Readiness Level
TO	Take-Off
TOM	Take-Off Mass
ToR	Terms of Reference
TOW	Take-Off Weight
TRL	Technology Readiness Level
TUAV	Tactical UAV
UA	Uninhabited Aircraft
UA	Unmanned Aircraft
UAS	Unmanned Aircraft System
UAV	Unmanned Aerial Vehicle
UCAS	Unmanned/Uninhabited Combat Aircraft System
UCAV	Unmanned/Uninhabited Combat Aerial Vehicle
UK	United Kingdom
UML	Unified Modelling Language
US	United States (of America)
USA	United States of America
USC	United States Code
USSP	U-Space Service Providers
UTM	Unmanned Traffic Management

UV	Unmanned Vehicle
VLA	Very Light Aeroplanes
VLR	Very Light Rotorcraft
VMO	Maximum Operating limit speed
VNE	Never Exceed Speed
VTOL	Vertical Take-Off and Landing
VTP	Vertical Tail-Plane
WoT	Web of Things
W3C	World Wide Web Consortium
xAI	eXplainable AI
XML	eXtensible Markup Language
XSD	XML Schema Definition

1. INTRODUCTION

The central topic of this PhD thesis is the conceptual design of fixed-wing Remotely Piloted Aircraft (RPA). As it will be seen in more detail along this introduction, the main areas of research developed in this dissertation are:

- 1) The investigation of the field of RPA conceptual design.
- 2) The assessment of the current landscape of topical areas which are tightly related with the aforementioned subject, such as those of regulations and computerised design environments.
- 3) The development of novel initial sizing methodologies for the first stages of fixed-wing RPA design.

With the purpose of contextualising and delimiting the scope and areas of work covered in this thesis, along these first pages an overview of key terms and topical considerations related to them shall be expounded.

RPA can be considered as a type of Unmanned Vehicle (UV), in which the vehicle which is being operated remotely is an aircraft. This vehicle is a part of a broader system, the Remotely Piloted Aircraft System (RPAS), which is composed by different interconnected elements and their interfaces. These components operate in a coordinated manner to achieve the intended operational mission. These other elements include, amongst others: the Payload (PL), which may at times be considered part of the aerial vehicle; the Ground Control Station (GCS); launch and recovery systems; and even the data link and other communication systems and protocols. The payload is the element which performs the more immediate task related to the intended mission (image acquisition, communication relay, atmospheric sample gathering, etc.). However, it is the RPA which enables the payload to be carried to the point, area or path where it can perform its task. Furthermore, the RPA provides power to the payload, enables its communication with the GCS, and it is also tasked with ensuring that key flight parameters (such as height above ground or airspeed) remain within adequate intervals to allow the mission to be accomplished. Further details on the different elements of the RPAS system, their purposes and interfaces can be found in (1; 2; 3; 4).

It should be mentioned that several terms and definitions have been used to name and describe both the air vehicle, as well as the full system. Details on the different concepts and definitions employed in this field are found in the works of (2; 5; 6). Some of the various terms employed both for the air vehicle and for the system, as described in the previously cited references, are summarised here. In most cases, one of the key considerations for an air vehicle to be defined as an RPA or any similar terms is that it must be recoverable after completing the mission. Furthermore, it should be highlighted

that parallels can be drawn between a term used for the air vehicle (for instance, RPA) and the equivalent concept referring to the full system (for example, RPAS).

- **Terms employed for the air vehicle:**

- **Unmanned Aircraft/Uninhabited Aircraft (UA) and Unmanned Aerial Vehicle (UAV):** these terms were coined in the military field and they refer to a flying machine which does not carry a human pilot on board. Depending on the source, subtleties between different definitions might be seen. For instance, the USA Department of Defense (DoD) considers an unmanned aircraft as "*an aircraft that does not carry a human operator and is capable of flight with or without human remote control*", whereas the United Kingdom (UK) Ministry of Defence (MoD) defines them as "*an aircraft that does not carry a human operator, is operated remotely using varying levels of automated function, is normally recoverable, and can carry a lethal or non-lethal payload*" (5). Other definitions can be found depending on the documents from the aforementioned organisations which are consulted.
- **Remotely Piloted Aircraft (RPA) and Remotely Piloted Vehicle (RPV):** these terms are usually employed to highlight the presence of a remote pilot who can control the aircraft (2). The notion of RPA is employed by the International Civil Aviation Organization (ICAO) to define an "*aircraft in which the pilot in command is not on board*".
- **Other terms that refer to the aircraft include:** drone (term used both in French and English), and Autonomous Aerial Vehicle (AV). There are further terms that can be employed depending on certain characteristics of the aircraft, such as Unmanned/Uninhabited Combat Aerial Vehicle (UCAV) which is used for UAV with strike and attack functions and payloads, Organic Aerial Vehicle (OAV), or Micro Aerial Vehicle (MAV), to name a few (6).

- **Terms employed for the full system:**

- **Unmanned Aircraft System (UAS):** this concept is linked to the aforementioned ones of UA and UAV, and it was introduced by the United States of America (USA) DoD, followed by the Federal Aviation Administration (FAA) and the European Union Aviation Safety Agency (EASA) (2). The USA DoD defines this term as "*that system whose components include the necessary equipment, network, and personnel to control an unmanned aircraft; also called UAS*", and the UK MoD as "*a system, whose components include the unmanned aircraft and all*

equipment, network and personnel necessary to controlling the unmanned aircraft” (5).

- **Remotely Piloted Aircraft Systems (RPAS):** the definition given by ICAO for this term, complementary to that of RPA, is: *“a set of configurable items formed by an RPA, its remote control station associated (RPS - Remote Pilot Station), the required system-link command and control and any other item required at any point during the operation of the flight” (2; 5).*
- It is noted that usually the terms UAS and RPAS are employed interchangeably (5). In the same vein as for the air vehicle, other terms can be found depending on the particularities of the system, such as that of Unmanned/Uninhabited Combat Aircraft System (UCAS) for those systems including anUCAV as the air vehicle.

In this thesis, the main terms employed shall be RPA and RPAS, but in a broad sense and for the purposes of this research, they are employed without loss of generality with respect to some of the other concepts mentioned above. At some points, such as for instance when referring to a particular regulation or other reference, the term employed therein shall be prioritised. Additional information on the aforementioned concepts and definitions, as well as their subtleties and origins, can be found in (2; 5; 6).

This thesis is focused on the RPA, that is, the air vehicle component of the system. The main purpose of the research presented here is to develop new methodologies for the initial stages of RPA design. The design process can be considered as the set of activities which start from the initial requirements with which the aircraft must comply, and through the application of a series of procedures, it reaches as an output the manufacturing blueprints for an aircraft which complies with the intended requirements that were stated at the start of the process (7; 8; 9). This synthesis approach is very distinct from an analysis process, which starts from a pre-defined aircraft with its parameters and characteristics already defined and seeks to estimate its performance and capabilities. The scope of this thesis is focused on the conceptual design stage, and particularly on the initial sizing process, which corresponds to the first steps of the conceptual phase and also of the full design workflow. The objective of this phase is to employ the initial requirements to arrive at an initial vision of the aircraft’s concept, which is a simplified definition that will be refined in further stages. Initial requirements typically include mission specifications, usually defined in terms of range, R , endurance, E , and cruise speed, V_c , among other variables; as well as applicable airworthiness requirements as prescribed in the regulations, such as the minimum steady rate of climb, RC .

In Figure 1-1, a schematic overview of the design process is illustrated, highlighting the area that is the focus of this thesis. Further on within this text, particularly in chapter 2, more background shall be given on the design process, its stages, and the typical methodologies employed in each of them.

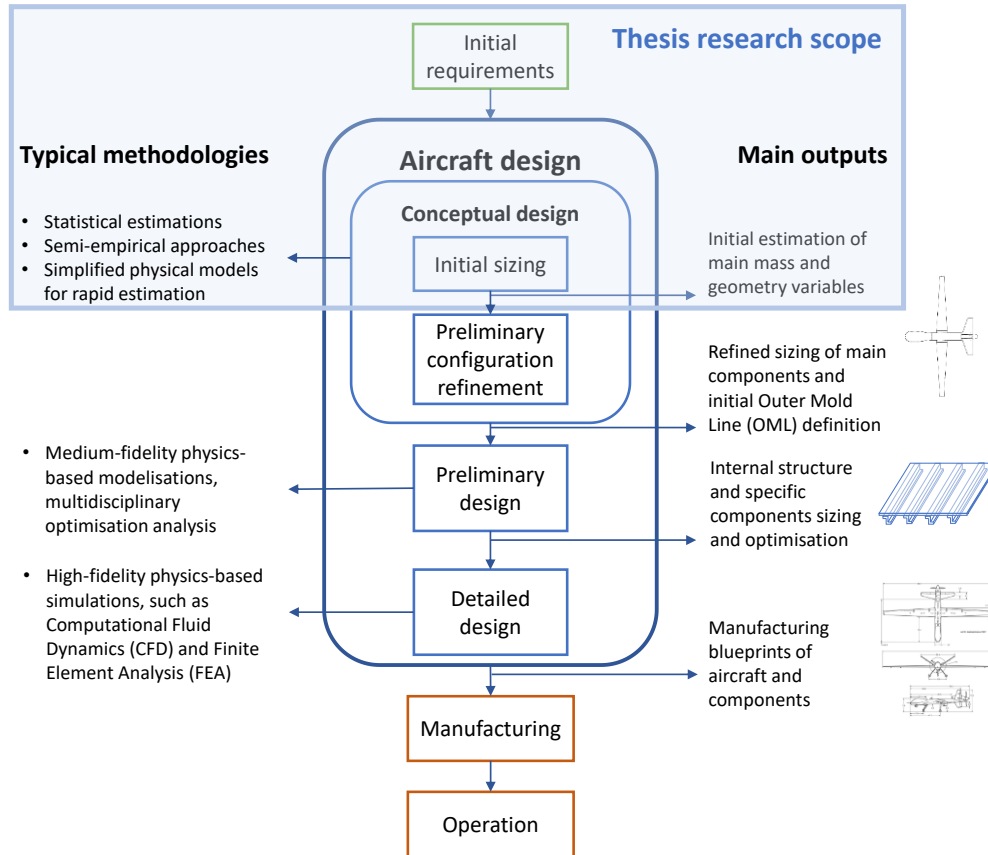


Figure 1-1. Schema representing the different phases of the design process and their context, as well as the scope focus of this thesis.

One of the main challenges pertaining to conceptual design is that, at this point, hardly any information on the aircraft to be designed is yet available, with the space of potential design solutions being large. The designer requires methods and tools to aid in the selection of the most promising design candidates, so that these continue on to further design stages where they will be refined and studied in more detail. Considering the previous point, the use of rapid procedures based on statistical approaches or simplified physics-based methods are key. The aircraft concept which is the main output of this stage is usually just defined by a handful of parameters (8; 10), typically covering the key design weights as well as the main dimensions of its key components, such as the wing, tail surfaces and fuselage. Finer details such as the wing twist distribution, the location and sizing of control surfaces and tabs, and the precise geometry of the nose and rear-end, are usually defined at later stages, using as baseline the estimations made during initial sizing (11). Even if the aircraft is yet only defined at a relatively simple level, the main strength of conceptual design analysis methods is that they allow to check the feasibility of the

design concept in a rapid manner, allowing to perform many design iterations in a short time and also permitting to compare various design alternatives in an agile manner.

The early aircraft definition reached at the end of the initial sizing step serves as the starting point for future stages, where the breadth of design space that is explored is much smaller, and focused in the vicinity of the already obtained initial geometry. In spite of the simplicity of some of the models employed at the conceptual stage and the low information of the aircraft which is available, the decisions taken here have far-reaching influence in the later stages of design, and their impact on the feasibility and efficiency of the final product is outstanding (8; 11; 12). Therefore, the investigation of methods and tools that can aid the designer in making the right choices at this point constitutes a remarkable area of research in aircraft design. The relevance of the conceptual design stage and its impact on further design phases are further explored within chapter 2.

As it will be seen along the first chapters of this thesis, there is currently room for improvement in the area of conceptual design methodologies for RPA. There are both similarities and differences between traditional manned aircraft and typical state-of-the-art RPA, and this extends to the design processes for each air vehicle type (13). In many cases, it is not feasible to directly employ for the development RPA the more mature initial sizing approaches that have been developed for manned aircraft, such as those expounded in classical aircraft design references (7; 8; 9; 11; 14). This is due to the many differences between both types of aircraft, including but not limited to: mission types, flight profiles, general configuration arrangement, typical geometries, applicable regulations, usual flight Reynolds number range, and characteristics of external elements, among many others. Thus, many methodologies that have been developed for manned aircraft would not be directly applicable in the field of RPAS, and relevant conceptual and quantitative discrepancies could likely occur, unless the sizing procedures are carefully adapted. This viewpoint of questioning the applicability of existing design processes and methods when dealing with RPA, and of developing new approaches when possible, is widely recognised among current authors of the field of manned aircraft and RPA design (6; 10; 15; 16; 17; 18; 19). Considering the above, it is seen that the development of original conceptual design approaches for RPA would constitute a remarkable asset for the initial design activities of these aircraft. This idea sets the key goal of the thesis, which is to develop novel initial sizing methods for fixed-wing RPA design.

Before tackling this goal, it is key to assess the current status of techniques of aircraft and RPA design. Thereby, the first step undertaken in this research shall consist in conducting a state-of-the-art overview of the current state of RPA design approaches for the initial design phases. One of the foremost characteristics of the field of aircraft design is its multidisciplinary nature. Depending on the stage of the design under consideration, and the intended scope of the design methods, several different disciplines may be involved in the aircraft synthesis and sizing. Thereby, this evaluation of the literature shall cover diverse topical areas and disciplines related to the design process, with particular

emphasis of those which are more typically used in the first stages of design, so as to detect potential gaps which can then serve as the focal point of the investigation developed in this thesis.

Aircraft design is a highly interconnected field, which is also linked to several other topics affecting aircraft development and operations. In the broader field of RPAS, as it will be discussed later on, there are many remarkable topics that are currently at the forefront of research and development of these systems. In particular, three topics stand out that have noteworthy links with design, and which also constitute relevant research areas in relation to the above-mentioned state-of-the-art overview and gap analysis:

- 1) Airworthiness regulations
- 2) Computerised design environments
- 3) Potential applications of Artificial Intelligence (AI) in design.

These will be analysed in detail within this thesis. Their prospective connections with RPA conceptual design approaches shall be explored, so as to then investigate and evaluate remarkable opportunities and challenges in their connection with design activities for these aircraft.

After assessing the overall RPA state-of-the-art, and the three outstanding topical areas mentioned above, the aforementioned goal of the thesis can then be addressed, which as stated beforehand, is set on the development of novel conceptual design methodologies for RPA. In particular, these shall focus on three main areas, the selection of which is informed not only by the essential disciplines in the first stages of design as supported by previous works, but also by the findings from the above-mentioned reviews, gap analyses, and assessments conducted within this thesis. These three areas are:

- 1) Estimation of new statistical trends for use in RPA design.
- 2) Procedures for the systematic extraction of design criteria from airworthiness regulations and their integration in RPA initial sizing approaches.
- 3) Development of analysis and synthesis methods for multi-role RPA design.

The design methodologies will be developed taking into account key gaps within the current state-of-the-art, and they shall factor in the main differences of RPA when compared to manned aircraft. Their development is accompanied by several application cases which serve to validate these approaches and to showcase their capabilities. Furthermore, their combined use in an overall design process which reaches the goals of the initial sizing stage as laid out in Figure 1-1 shall also be proposed and demonstrated.

Thus, between the overall overview of the RPA design literature, the research on the aforementioned three areas of particular interest which link with design approaches, and

then the development of original design methods in relation to the above-mentioned disciplinary areas which will be considered in the design methodologies, the scope of the thesis is broad, covering various topics. The thesis is structured in four parts so as to order its contents, with each of these containing one or more chapters, which overall follow the process and steps outlined above. A more detailed account of the thesis structure and flow will be described later on within this introduction.

As an additional note regarding the scope of this research and the nature of the initial sizing approaches to be developed, the focus in this thesis is on systematic design methodologies. One of their foremost characteristics is that the inputs (in this case, the initial specifications) are part of the degrees of freedom of the method. Thus, the design methodology can be applied on distinct initial requirement sets, and the output aircraft in each case would be different, as it has to be designed according to the specific requirements of each application case. Thereby, the applicability of these systematic design methodologies is relatively broad. In contrast, other works have studied the design of a specific RPA, starting from a pre-defined set of initial requirements. These works usually employ ad-hoc design approaches, which may at times follow some steps of systematic methodologies, but depending on the particular case, at times might opt for alternative procedures. Both types of approaches are useful in their particular areas of use, and they are also interrelated, since broadly applicable design methodologies can then be used in specific design cases, and particular design applications can be used to validate the former. More details on the differences between both approaches shall be given later in the text.

Having laid out the main topical focus, objectives, and scope of the thesis, the remainder of the introduction is structured as follows. First, in section 1.1, some contextual information shall be given on the current state of the field of RPAS, along with perspectives regarding its future development. Then, in section 1.2, the main distinctive characteristics of RPAS shall be expounded. Here it will be seen that many of these aspects are very different when compared to traditional manned aircraft, as it has been anticipated. In section 1.3, an overview of the main current challenges in RPA conceptual design shall be presented. This will then link with the main motivation and objectives of the research presented in this thesis, which have already been outlined here, but will be further emphasised and specified in section 1.4. Then, section 1.5 presents the main contents and structure of the remainder of the thesis, and finally section 1.6 provides an overview of the publications associated with the research conducted along the doctoral studies in relation to the content of this thesis.

1.1. Current state and outlook of RPAS

Albeit RPAS have existed for a long time (5), it has been in the last two decades when they have experienced a pronounced growth in interest, research, development and investment. This trend is not only ongoing, but even accelerating, and the impact that

these systems are having in different areas of aviation is also becoming more pronounced. From the heightened effort from Aviation Authorities to regulate the field of RPAS in order to ensure their safe integration into the aviation system; moving on to the interest from operators due to the ever increasing mission diversity that can be tackled with RPAS; and on to the application of novel technologies and AI in different areas; it can be seen that RPAS are one of the most dynamic areas within the aviation industry in recent times. This section provides a brief overview on the main areas of interest of these aircraft and on various metrics showcasing their current status.

It could be said that two main drivers have led to the growth of interest on RPAS systems in recent times:

- 1) The recent technological advancements in many areas that intertwine with the field of RPAS have enhanced the capabilities, opportunities and efficiency of these systems. Domains such as those of sensors, payloads, airframe systems, flight control systems, component miniaturisation, advanced materials, new propulsion and deployment techniques, etc., have all contributed to improve the effectiveness and efficiency of RPAS, thus making these systems more appealing to seek solutions to diverse applications such as remote sensing, environmental research, traffic monitoring, Search and Rescue (SAR) and many other missions (1; 20; 21). Also belonging to this area, it has been noted that the low development costs, fast fabrication types and rapid prototyping capabilities of these systems are also among the major drivers explaining the recent surge in the interest and deployment of these systems (18; 21).
- 2) There has also been an emergence in new applications and missions where the specific advantages of RPAS can be leveraged, which through time have become more diverse, thus augmenting the potential applications of RPAS (21; 22). Within military applications, the emphasis is usually on missions usually labelled as D3: “Dirty, Dull and Dangerous” (1; 6; 23). The fact that the pilot is not on board of the aircraft reduces the risk to human life in these kinds of operations when using RPAS. In the civil area, the above-mentioned mission types are also among the most typical uses of these aircraft, such as their use in radioactive environments or hazardous weather conditions. Furthermore, the compactness and ease of deployment of these systems also make them appealing for other types of applications, such as scientific and commercial missions. Some of the many uses of RPAS in these areas include scientific data collection, weather forecast and meteorological monitoring, coastal monitoring, earth science research, disaster prevention, infrastructure inspection, cargo delivery, photography, and agriculture (6). In some cases, these can intersect with the aforementioned D3 mission types, such as in the development of photogrammetric research in Antarctic terrain (24) or the collection and analysis of the research of volcanic environments (25). Further key applications of RPAS include Intelligence,

Surveillance and Reconnaissance (ISR), border surveillance, communications relay, and fire hazard surveillance (26). It is highlighted that most of these applications seek to leverage the specific characteristics of RPAS, as commented above, so previous authors consider that the niche filled by RPAS is, in broad terms, different to that of manned aviation, albeit there can be some overlap (23). More information on the wide array of potential applications of RPAS can be found in (1; 6; 21; 26; 27).

The recognition of the promising opportunities of RPAS has motivated a substantial increase in the resources and production values destined to these systems. This way, current forecasts predict that the civil market will grow from a market value of \$8.2 billion up to \$19.5 billion within the next ten years (28). A similar trend is predicted in the military domain, with annual spending increasing from \$15.3 billion up to about \$25.4 billion in the following ten years (28). Aside from these metrics, which are more focused on economic aspects, there are others which allow to showcase the growth that will be experienced by these systems. One of the most relevant trends is analysed by the FAA within their annual Aerospace Forecast. In the most recent version, it is seen that registration of RPA will increase in the following years in all three analysed categories: Part 107-recreational, Part 107-commercial, and Part-49 large UAS registration (29). These correspond to different regulatory paradigms employed in the USA for operations of RPAS, as it will be further explored along this thesis. Of particular interest is the latest category, for which an accelerated growth is predicted along the following next years. This coincides with the forecasts of the European Commission (EC), which concluded that the area of RPAS below 150kg of Maximum Take-Off Mass (MTOM) would constitute the most dynamic category in the upcoming times (30). Figure 1-2 showcases a sample of the available data representing these growth trends.

Following this trend, and in view of the exponential growth in the development of these aircraft and their heightened presence within the airspace, the different Aviation Authorities have increased their efforts and are currently amidst an intense rulemaking activity since some years ago, seeking to lay out standards and recommended practices for the design, production and operation of RPAS, thus paving the way for their safe integration within the current aviation paradigm. Of particular interest is the activity which is being carried out by the main Aviation Authorities with marked international influence, specifically the ICAO, the EASA, and the FAA, all of which have greatly advanced in the integration of RPAS within regulatory considerations in the last years (23). In parallel, many National Aviation Authorities (NAAs) of different countries have also carried out rulemaking activities within the past years so as to be up to date with the emergence of RPAS (31).

The number of RPAS which are currently in development, production or deployment constitutes another remarkable metric to evaluate the current state of this field. In the database compiled by (32), it is shown that there are currently over 2000 systems in the

conditions mentioned beforehand. It should be noted that approximately half of them are fixed-wing RPA, which are the ones considered within the boundaries of the research conducted in this thesis.

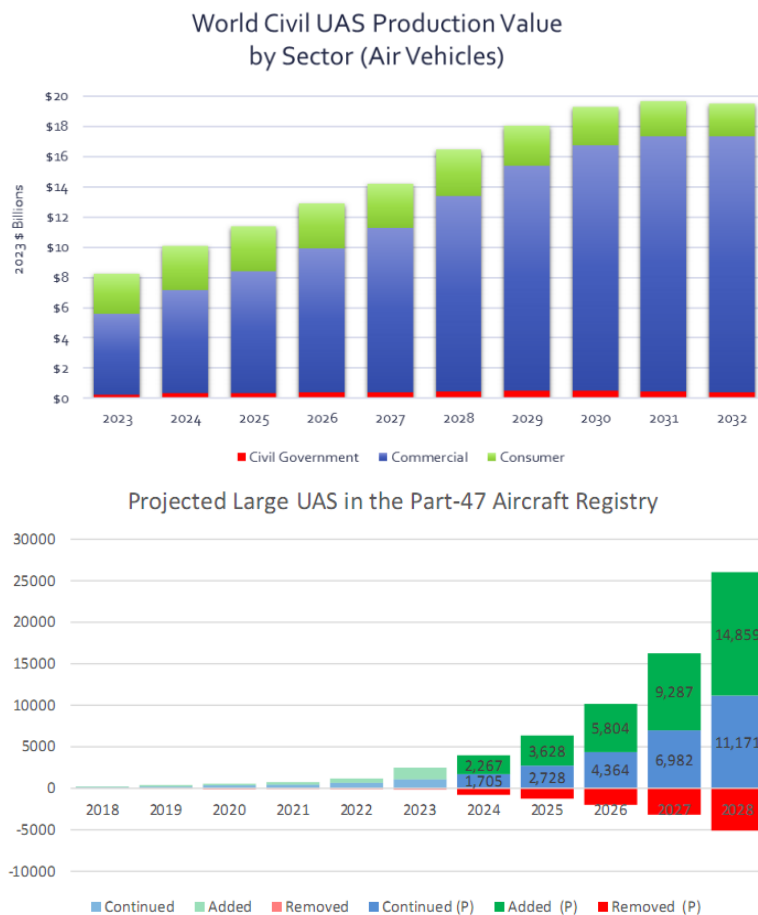


Figure 1-2. The figure above represents the worldwide civil RPAS production value by purpose of application, obtained from (28). The figure below showcases the estimated registration of large RPAS within the Part-47 registry in the USA, obtained from (29).

Furthermore, research activity in the field of RPAS has also experienced an outstanding increase in the past years. RPAS design, which is the main topic of this thesis, is only a part of the full range of publications and projects related to different areas of these systems. At several points along this thesis, analyses on the open literature of RPA design and related areas shall be conducted, at which point the volume and dynamism of the academic field of RPAS will be more clearly seen.

Overall, it can be seen that the increasing opportunities that RPAS are offering, with an ever-increasing range of possible applications and many technological advancements boosting their growth, is favouring their impact and development in many different areas, including design, operations and regulations.

1.2. Outstanding characteristics of fixed-wing RPA

As it has been brought forward in advance within the first part of this introduction, fixed-wing RPA present a very distinct set of characteristics which differentiate them from traditional manned aeroplanes. Several of these aspects precisely constitute some of the main advantages that the RPA can leverage in order to enable their flexibility and the wide variety of applications which they present. In this section, a rapid overview of these features shall be expounded. The focus shall be on the air vehicle component of the system. There are also some outstanding characteristics of the regulatory paradigm of RPAS, in relation to its development, priorities and main rulemaking philosophies, which are remarkably different from those of the traditional aviation paradigm. Those aspects shall be commented in detail later within the main content of the thesis.

From an application and operations perspective, RPAS present several characteristics that differentiate them from conventionally-piloted aircraft, and which may make them particularly suited towards certain applications. One of their most outstanding features, which has been highlighted by previous authors in the field (1; 2; 6; 21; 27; 33; 34), is the large array of missions that these systems can accomplish, as already outlined in the previous section. Whereas some RPAS are designed with a particular kind of mission in mind, one of the most promising traits of these systems is the capability of the same RPAS being able to accomplish a variety of missions with different characteristics (35). This can be achieved, for instance, by having a single RPA and several interchangeable payloads that serve to accomplish distinct missions (6), which is a widespread approach among state-of-the-art RPAS, as quantified in the work of (36). In the frame of this thesis, it is relevant to highlight these aspects related to the mission and applications of RPA, as mission specifications are paramount among the initial requirements which serve as the main inputs of the design process. As seen above, RPAS do not only present a remarkable mission variety, but the possibility of using the same air vehicle with different payloads to accomplish distinct missions gives rise to multi-mission capabilities, which constitute another key strength of these aircraft systems. To fully leverage this option, it would be essential for the air vehicle to be designed considering all of the missions concurrently, so as to ensure that the final resulting product can achieve all of the applications that were part of its initial specifications.

Following on with the topic of missions of RPA, and in this case from a quantitative standpoint, the aforementioned variety in applications of these aircraft can also be illustrated through the ranges of values that key performance variables of RPA can take. Albeit these numbers depend strongly on the type of aircraft, configuration and powerplant, amongst other factors, some values are shown to provide a general perspective on the aforementioned variety. For small RPA conducting short-range missions, typical values of range, R , from less than 10 km to up to 70 km can be found, with representative numbers for endurance, E , having an upper boundary of a couple of hours in most cases. On the other hand, aircraft performing long-endurance missions,

such as those of the Medium Altitude Long Endurance (MALE) category, show values of endurance which can be in excess of 40 hours (5; 21). Medium-range tactical aircraft would fall in between these two extremes. Furthermore, cruise speed values, as declared by manufacturers and official data compilations such as (32; 37), can range from 50m/s up to almost 300m/s. These ranges of values further emphasize the aforementioned flexibility of RPA, both in design and operations.

Moving on to aspects that are more connected with the airframe design itself, the extraordinary diversity of RPAS design approaches and solutions can be perceived at first glance upon seeing the large variety that these aircraft present in relation to their overall layout and powerplant types. Albeit the focus of this thesis is set on fixed-wing RPA, it should also be stated that there are many types and configurations of RPA outside of them, for instance for rotary-wing, flapping wing, and hybrid fixed-rotary-wing aircraft types, as well as for lighter than air aircraft, a detailed exposition of which can be consulted in the works of (1; 6; 21; 33). Within the realm of fixed-wing aircraft, while traditional manned aeroplanes that are envisioned for similar operations tend to present comparable general layouts (for instance, the predominant conventional and T-tail layouts for transport aircraft), in RPAS this is not the case, as even for the same mission types, very varied solutions in terms of configuration can be seen. This remarkable diversity in the architectural characteristics of RPA airframes when compared to manned aircraft has been highlighted in previous works (21; 33; 35). An example of this variety, along with the powerplant diversity, can be seen in Figure 1-3, which showcases various existing RPA.

There are many other qualitative aspects which constitute additional differences in design aspects of RPA that can be seen among different platforms. For instance, the landing gear configuration, which is also related to the type of launch and recovery methods employed with the RPA; and the wing planform type, are aspects that showcase a great variety among different RPA designs, and they can also partly be seen in Figure 1-3. Yet another of such aspects is the propeller type, which can be of fixed pitch, adjustable pitch, or variable pitch. Another such dimension of variability is constituted by the payload type. As it can be expected when taking into account the large variety of missions that RPAS can conduct, there is a large variety of payload types, with different geometrical and mass properties.

Moving on to some quantitative aspects, but also directly linked with the design itself, RPA have been noted to present a significant variety in mass and geometric variable values. Of particular interest is the fact that in many cases these numbers would not be feasible in manned aircraft. However, for larger RPA, there can be certain overlap with the ranges of values present in manned aircraft. In this way, the MTOW of RPA can range from values lower than a kilogram to tens of tonnes, and values of wingspan are found from less than one metre, up to those typical of commercial transport aircraft.

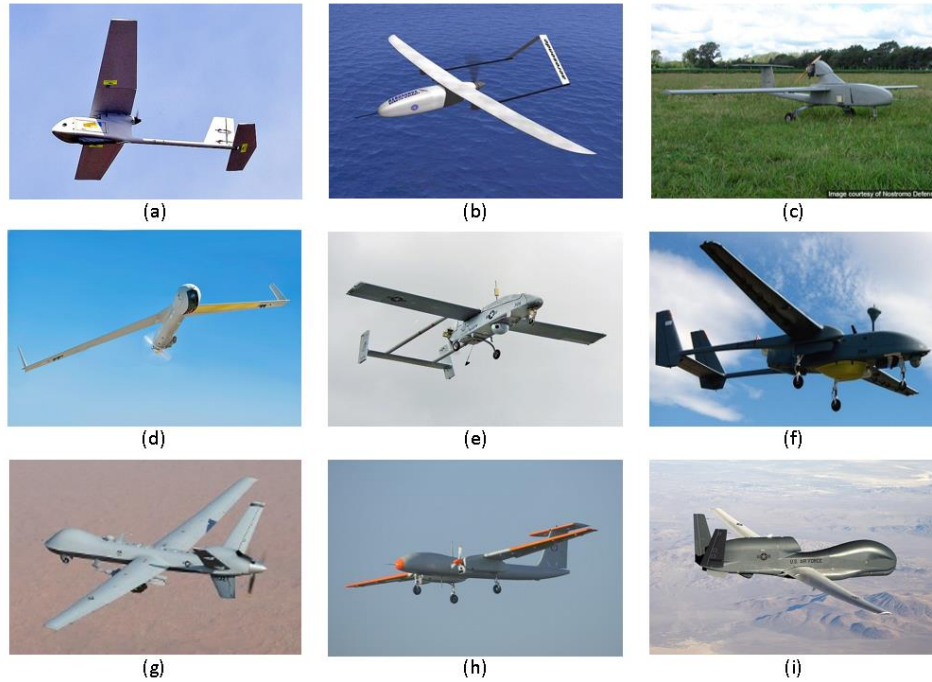


Figure 1-3. Various examples of fixed-wing RPAS, showcasing the variety in layouts and powerplants, among other aspects. (a) RQ-11 Raven, with conventional tail, single boom and electric powerplant, (b) Aerosonde, with inverted V-tail, double tail booms and piston engine, (c) Nostromo Yarara, with T-tail, single tail boom and piston engine, (d) ScanEagle, with tailless configuration and piston engine, (e) Pioneer, with H-tail, double booms and piston engine, (f) Heron 1, with H-tail, double booms and piston engine, (g) Reaper, with Y-tail and turboprop engine, (h) Tapas II, with T-tail and twin piston engines, and (i) Global Hawk, with V-tail and turbofan engine. All images obtained from commons.wikimedia.org.

Seeing the outstanding diversity of RPAS in the different dimensions outlined above (missions, general layouts, powerplants, etc.), several classifications have been proposed in previous works to group these systems into more homogeneous sets. They constitute a fundamental asset in the study of this field, particularly when performing statistical analyses, as it will be explored in detail further along this thesis. Each of these classifications prioritises different features to perform the categorisation of RPAS. Some outstanding categorisation schemas include:

- **Classification attending to size, performance and capabilities:** this categorisation is notably extended, and tends to appear in different references with a distinct number of categories and dissimilar classification criteria (1; 5; 6; 21; 32). In fact, it has been stated that the frontiers among the different categories and the categorisations themselves have been changing along time with the evolution of the technological capabilities of RPA (1). However, it is useful to provide a rapid overview of the characteristics of the air vehicle and its typical missions. Common categories are: Nano Air Vehicles (NAV), Micro Air Vehicles (MAV), Small UAV, Tactical UAV (TUAV), Low Altitude Long Endurance (LALE), Medium Altitude Long Endurance (MALE), and High Altitude Long Endurance

(HALE), albeit depending on the author, others can be found. Common variables used for the classification include the range, endurance, MTOM, and flight altitude, among others.

- **Classification according to airframe type:** tightly related with the approach through which the RPA generates the lift force and also to the take-off, cruise and landing performance. This categorisation comprises the classic fixed-wing and rotary-wing types, while also including in certain cases other more unusual approaches such as hybrid aircraft, tilt-wings, flapping wings, and ducted fans, among others (1; 5; 32).
- **Classification according to overall layout:** it is based on the aforementioned outstanding variety of configurations which can be seen in RPA designs. It usually considers criteria such as the tail type and the kind of tail union. Albeit this classification is not as extended in this field when compared to others, it has been considered in the survey of (33) and has revealed significant trends in previous work focused on design methods (38).
- **Classification attending to powerplant:** this type of categorisation has been employed beforehand in works focused on the design of RPA (6; 36; 38; 39). The most usual and representative categories include electric, reciprocating, and turbine powerplants, with other powerplant types such as hybrid and fuel cells also being considered in some works.
- Many other such categorisation schemas exist, such as attending to the use class (civil, military, dual) (32), focusing on classifications as laid out by key stakeholders such as the North Atlantic Treaty Organization (NATO) categorisation (40), or using a combination of other categorisations (21; 33).

Considering this overview, it can be seen that, overall, RPA present a great variety of operational and design characteristics. From the perspective of the aircraft designer, this results in a potentially large design space to explore. This can constitute both an advantage, resulting in a great variety of potential feasible solutions; but it can also be a challenge, as the increased breadth of the design space as well as the selection of the ideal configuration for the specific application can constitute additional hurdles in the development of design methods to aid in navigating this landscape, as it will be further discussed in the following section.

1.3. Current challenges in RPA conceptual design

From the previous sections, it has been seen that RPAS present a promising array of opportunities for applications and missions, which are accompanied by a large variety in their possible design characteristics. To develop RPA which can fully leverage the potential that these types of aircraft can offer, it is needed to design them taking into

account their particular characteristics. This requires the establishment of rational procedures applicable to these aircraft through which the designer can reach the definition of the air vehicle in such a way that it satisfies its initial requirements.

However, the development of design methodologies for RPAS faces significant hurdles, with many of them being related to the singularities of these aircraft (13). The expansive and varied possible space of missions which RPAS offer, along with the aforementioned equally large diversity in the conceivable design characteristics of these aircraft, may constitute remarkable challenges for the aircraft designer. This is due to the space of potential designs being larger and more complex, so it can be expected that the methods to aid the designer in performing initial estimations and selecting the most promising design options also need to be more involved. Furthermore, as already brought forward in section 1.2, RPA present many differences when compared to traditional manned aircraft, which are also expected to result in significantly distinct design considerations and procedures (19). At this point, it should be highlighted that the field of manned aeroplane conceptual design is very mature, and albeit there is still work to be done in specific areas, the level of development of the methodologies employed there is very high, and those approaches have been tested to a great extent. However, the aforementioned distinctions between RPAS and manned aircraft render many of the proven methods for the latter not directly applicable to the field of RPA, as supported by various investigations in the state-of-the-art of RPAS design (6; 10; 15; 16; 17; 18; 19). This constitutes an added challenge, as original methods have to be derived for RPA which account for their particularities (17; 41).

As the main focus of the thesis is set on the development of conceptual design methodologies for RPA, firstly, the main challenges that the designer must surmount not only for the development of particular RPA, but also in the development of systematic design methodologies for these aircraft, should be analysed. Albeit many additional insights, which will also have a more specific nature than those commented here, shall be found along the research conducted in the thesis, this initial discussion on the challenges commented below allows to provide the main contextual background on the particular obstacles which will be further developed and addressed along the thesis.

Thus, a summary of some of the current challenges in RPA design, mainly focused in the initial stages of design, as is the main focus of the thesis, is outlined below:

- **Variety in mission types and performance characteristics:** while this constitutes one of the most valuable assets of RPAS, it can also result in a noteworthy challenge for the designer. As it was outlined at the start of the introduction, and will be seen with more detail later on, the initial requirements are the main input of the conceptual design process. Mission-related aspects are among the most important parts of these specifications, as they establish the objective operation for which the aircraft is designed. When compared to other types of aircraft, here the potential variety in the key values of the mission

parameters, the mission profile geometries, and even the flight laws employed during the flight can present a much larger diversity. This variability in the aforementioned dimensions is caused by the outstanding array of different operation types of RPAS, from ISR, to SAR, to cargo delivery, among many others, each of which requires specific mission profiles and different considerations. Previous research works in the area of RPAS design have highlighted the diversity in RPAS operations and flight conditions as a key hurdle for the development of new design methods for these aircraft (35), and the differences with respect to operations of manned aircraft have also been pinpointed as requiring the development of new performance analysis tools for these diverse operational scenarios (17). Thereby, flexible methodologies which can account for several mission models would be required to integrate this larger variety of mission specifications in the design process and to be able to analyse the performance of an aircraft attending to this heterogeneity.

- **Development of multi-mission aircraft:** adding to the last aspect, aside from the potential variety in the mission definition parameters for which the RPA is being designed, the multi-role capability of these aircraft would constitute an added challenge. This concept means that the same aircraft has to be sized to ensure that it can comply with different design missions, most possibly with dissimilar payloads, flight profiles, flight laws, and performance objectives. For instance, a cargo mission for which the critical performance goal is the range from the take-off point to the delivery one is notably different from an ISR one where the key goal is to achieve a certain endurance over an observation point, which most possibly has to be reached with an ingress flight from the take-off point, and the aircraft then has to return to base for recovery. As it will be seen in the thesis, multi-role conceptual design approaches are scarce in the current literature, even in the field of manned aircraft design. This, coupled with the aforementioned diversity in RPAS missions, results in a noteworthy obstacle for the design of RPA.
- **Lack of applicability of statistical data of manned aircraft:** one of the paramount approaches within conceptual design methodologies is the use of statistical approximations and trends extracted from aircraft of the same type to that which is being designed. As information during the conceptual design stage is scarce, it is usually necessary to use empirical relationships or typical values for certain parameters in order to make the mathematical problem more defined (7; 8). Another advantage of these historical data is that they can be used as a cross-check to evaluate that the obtained results in the aircraft synthesis are believable (11; 39). Even with the advent of greater computational capabilities, research in new empirical relationships remains an extraordinarily active field of research in the area of manned aircraft design, as seen in recent works (42; 43; 44). However, as brought forward beforehand, RPA present ranges of values of certain parameters which are starkly different to those of manned aircraft. Thereby,

attending to this and also owing to additional differences between RPA and those aircraft, classic statistical values and relationships would not be applicable in most cases to RPA, as highlighted by previous investigations in the field (15; 18; 19; 39). In particular, in the work of (18) the direct reuse of trends of manned aircraft were demonstrated to yield inaccurate results in RPA, requiring adaptations to the methodology. Thereby, statistical data on RPA has to be gathered to obtain novel empirical relationships. However, this in itself has its own sets of challenges, as among other aspects which will be thoroughly explored later on in the thesis, the comparative lack of historical data with respect to the much more mature area of manned aircraft constitutes a relevant hurdle towards the estimation of new empirical trends for RPA conceptual design (35). In spite of this, previous authors in the field of RPA have remarked the advantages that the derivation of such novel empirical results could bring, and there is a high degree of research interest in this area (35; 36; 39; 45; 46; 47), so it can be argued that working towards surmounting the aforementioned obstacles constitutes a worthwhile effort.

- **Unsettled and dynamic regulatory requirements:** aside from mission objectives, regulatory requirements are also among the paramount specifications established at the onset of an aircraft design project (7; 8; 9; 48; 49). In the case of RPAS, as mentioned beforehand, the regulatory paradigm is currently a very dynamic area where many changes are underway. Thereby, and in spite of the intense activity being conducted by Aviation Regulators, and albeit some outstanding regulations are already in place, the regulations for RPAS are still overall under development. Even for the regulations published by now, the possibility of short-term changes should not be discarded. Furthermore, as it will be seen later in the development of this research, even when regulations are established, they present some key differences in their philosophy and approach when compared to manned aircraft. These not only require specific analyses, but it can also be regarded that they add a further layer of complication towards the integration of airworthiness requirements in the design process. All of this results in uncertainties and additional complications towards the integration of airworthiness requirements in the design process, which are not only essential to ensure that the resulting aircraft concept complies with these crucial prescriptions but are also an essential asset towards improving the safety of the resulting design.
- **Configuration diversity and widespread use of atypical layouts:** as it was commented before, and as seen in Figure 1-3, RPA do not only present a wide variety of layouts, which further expands the feasible design space and leaves the problem of RPA design less defined (35); but also most of the usual configurations seen in RPA would be considered atypical within the realm of manned aircraft. For instance, layouts such as the V-tail or the H-tail are labelled as unconventional

configurations within the field of manned aeroplanes, however they are observed commonly in the field of RPA, accounting for a large proportion of designs within this area (35). This variety in configurations requires further considerations in conceptual design methodologies. As an example, the diverse configurations could follow different design trends, which could require the aforementioned statistical analyses to be conducted on each of them separately. This could, for instance, result in issues of lower sample sizes when categorising both by powerplant as well as by overall layout. Other challenges associated both to the diversity of configurations and to the ubiquity of unconventional ones in the realm of RPAS shall be more thoroughly explored through the thesis.

- **Overall lack of applicable conceptual design methodologies:** this issue is related to many of the previous points. Overall, and not only focusing on RPA, authors in the field of aircraft design highlight that the applicability of the various analysis and synthesis methodologies found in the literature is mostly restricted to the scope considered in their development (11; 50). For instance, mass estimation methods should only be applied for aircraft with similar performance and layout to those which have been used to derive them (6; 9; 11; 51). In the case of unconventional configurations and RPA, which deviate significantly from traditional aircraft, the applicability of proven historical approaches for aircraft design can be debatable, and adaptations should be made with care (6; 10; 15; 16; 17; 18; 19). This consideration is not only applicable to statistical trends, but also to semi-empirical approaches and certain physics-based methods, as the hypotheses used to derive them in the case of traditional manned aircraft might no longer hold for RPA. Two examples are given below:
 - In previous works focused on semi-empirical approaches for drag polar estimation for RPAS in the conceptual design stage (52; 53), it was highlighted that traditional drag polar formulations, such as those given in the works of (7; 8; 14; 54), might yield inaccurate results when used for RPA. Thereby, adaptations to the conventional formulations were developed.
 - As another example which shall be developed further along this thesis, the usual hypothesis of employing the Bréguet Equation with a constant range factor, K , for the whole Payload-Range (PL-R) diagram of a commercial air transport aircraft (7; 51), might not be applicable to RPA taking into account their flight profile and mission diversity.

All of this results in the designer not being able to directly apply existing methods to RPA design. Furthermore, it has been noted that various previous efforts the area of fixed-wing RPA have employed trial-and-error approaches for design, which may not have enabled to achieve the desired levels of efficiency (21). The above points spark the need for developing novel or adapted approaches

particularly tailored for these aircraft attending to their singularities and which can improve the effectiveness and efficiency of the resulting aircraft concepts (17; 19; 41).

In order to address the lack of applicability of certain traditional design methodologies to unconventional configurations RPA, some previous works (12; 55; 56; 57) have emphasised the use of high-fidelity approaches, such as Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA), since their underlying foundations, models, and hypotheses might be more immediately adapted cover the particularities of RPA. These kind of methodologies are undoubtedly of extraordinary use in advanced design phases, where they provide results with a high level of accuracy which cover physical phenomena that are not accounted in early design steps. However, their longer calculation times hinder their application to the conceptual design stage, where the emphasis is on fast estimation and the exploration of a remarkably large design space. This is why, in spite of the recent advances in computational capabilities, there is still an outstanding demand for rapid estimation methodologies compatible with use in conceptual design. Recent works in the fields of aircraft unconventional configurations and of RPA have emphasised the development of novel sizing algorithms and rapid calculation approaches for the conceptual design stage of these aircraft (17; 58; 59; 60; 61), with these new methods being particularly adapted for these kind of air vehicles so as to ensure applicability. Once the initial stage of design is finished, and the design space is narrowed, the potential of high-fidelity approaches can be more adequately leveraged in the following design stages, which may use as the starting point of their calculations the previously found promising concepts, which can then be refined to advance on to the final design. Therefore, clearly there is the need for advancements and research both in rapid methodologies and high-fidelity approaches, so that each kind of method can be leveraged in the stage of the design process where the potential of each of them may be more adequately harnessed.

It should be noted that there are also many other areas in which RPA and RPAS differ from traditional manned aircraft, and which may constitute further design challenges for RPA. The discussion above has been focused on those hurdles which affect in a more direct manner the conceptual design stage, which mainly deals with the overall shape and configuration of the aircraft; basic geometric definitions of main components; and mass, aerodynamic and performance modelling aspects that can be captured through rapid analysis and synthesis approaches. However, as the design definition advances, more detailed considerations and other analysis disciplines, which are required to refine the initial concept, are incorporated. Thus, other challenges for RPA design which can be considered to fall within the scope of further design stages can include differences in airframe systems, internal equipment arrangement, flight control systems and autopilot design, communication aspects, and flight testing and data collection, among many others. Furthermore, aside from the aforementioned aspects which are directly related to design aspects, there are also a variety of relevant challenges in other areas within the field of RPAS, which also constitute main obstacles in the path towards leveraging their full

potential. Some of these further issues include but are not limited to: integration in non-segregated airspace, pilot training, autonomy, and collision avoidance among other aspects. However, the challenges and dimensions mentioned above would fall outside the scope of the thesis, as they are not directly related to conceptual design topics.

1.4. Research motivation and objectives

The overview conducted in the previous section has revealed that there are remarkable challenges to overcome towards the development of conceptual design methodologies applicable to the development of RPA and which can aid the designer to leverage the advantages of these systems. In spite of these difficulties, the outstanding potential of RPAS has driven a significant volume of research in the latest times to investigate ways in which to overcome these hurdles so as to provide procedures which can aid the designer in the development of these air vehicles.

This section lays out the main motivation and objectives of this thesis. As in the previous section on challenges in RPA conceptual design, some of the aspects mentioned here will be substantiated in more detail later on along the remainder of the thesis, particularly within chapter 2, which conducts a state-of-the-art analysis on the field of RPA design.

As it will be analysed in further detail later on within this thesis, a significant number of current contributions in the literature would fall within one of the following categories:

- **Works focused on preliminary design and optimisation:** the preliminary design stage is the one following the conceptual phase. Its objectives, characteristics, and main methodologies will be commented in detail later on within chapter 2. As an overview, it typically starts from the aircraft concept previously defined at the end of the conceptual step, and is focused on refining it through the use of medium or high-fidelity models, in contrast to the rapid estimation ones employed at the previous stage, and a larger number of disciplines are considered here (11; 51; 62). Whereas the conceptual design phase seeks to obtain one or more aircraft concepts which satisfy the initial requirements, the emphasis in preliminary design is on optimising these first estimates to achieve an enhanced design concept (41; 51; 63). Albeit the methods have a higher degree of accuracy than those employed in conceptual design, the design space explored in this stage is usually a reduced fraction when compared to that which has to be managed in conceptual design. Thereby, the challenges of each of the design stages are notably different, and one cannot substitute the other. An adequate selection of the initial point in conceptual design is a fundamental asset towards achieving a satisfactory optimisation behaviour and convergence on the desired point within preliminary design. Within the state-of-the-art, there have been previous efforts in the development of preliminary design and optimisation approaches for RPA, whereas there are fewer works that tackle

the conceptual design stage. Furthermore, in the preliminary design works, the initial optimisation point and the choice of the configuration (which is usually pre-defined in these cases) are typically not substantiated through the use of synthesis approaches employed at earlier design stages, leaving the conceptual design criteria employed to reach those decisions undefined, thus highlighting a gap in the earlier design phases.

- **Conceptual and preliminary design works of a specific RPA:** in these cases, the focus is not on the development of a systematic design methodology which can be broadly usable with many different RPA initial specifications. Rather, a specific design case is undertaken, with a pre-defined set of requirements. In these types of works, the sizing and/or optimisation is usually achieved through a combination of using certain steps from pre-existing systematic design methodologies, in some cases, directly using procedures of the manned aircraft design literature. Thereby, the approach is notably different to that which is sought to be developed within this thesis, which as outlined at the start of the introduction, is focused on the development of new systematic conceptual design approaches which can be applied to different design cases in a flexible manner, producing in each case a distinct initial concept as a result of the distinct objectives from which they are generated. These systematic methods can then be applied, within their applicability range, to a range of various design cases such as the ones commented beforehand.

These two previous lines of work within the current state-of-the-art have resulted in extraordinarily relevant advancements in the field. However, they would still leave a gap in the area of systematic conceptual approaches that can be broadly applicable to fixed-wing RPA with diverse initial specifications. As it was seen in section 1.3, RPA can have remarkably distinct requirements for their mission specifications, thus methods with a broad applicability range would constitute a fundamental asset for RPA design, as the results from particular design cases might not be generalisable to other scenarios. With respect to the preliminary design approaches that have been studied in previous works, these do not substitute the need for conceptual design ones, as methods that can explore the expansive design space available before establishing an initial optimisation point are essential towards making the appropriate initial sizing in the first stage, which as mentioned at the start of the introduction, is a key decision that has a fundamental effect in all future steps of the design process. The nature of conceptual design approaches is also fundamentally different, as they must allow a rapid concept generation and feasibility estimation, and should be able to manage the large variances in the design which can occur along the exploration of the expansive design space within the conceptual stage. Furthermore, advances in the area of systematic methodologies can help to ease the need for trial-and-error approaches which have been used previously in this field as mentioned beforehand (21). These systematic methods may also be applied to particular case studies of RPA design. Therefore, it can be seen that filling the above-mentioned gap does not only

allow to cover some design needs which presently show room for improvement within the field of RPA design, but it can also be expected to contribute to the two types of work which are currently more widespread in the open literature.

The aforementioned scenario sets up the landscape for outlining the research objectives of the thesis, which were already brought forward at the beginning of the introduction and will be defined here in a more precise manner, along with the motivations which have led to formulating them. It is noted that these objectives (OBJ) are tightly related to each other, and their sequence represents the organisation of the research conducted along the doctoral studies, with some of the specific objectives formulated within the higher-level ones emerging as a result of the findings resulting from the research of the previous ones:

- **OBJ.1: Conducting a broad overview on the current state of RPA design approaches.** The main purpose is to conduct a review at a coarse granularity level of the RPA design methods which have already been developed in this field. Much of the material found in the open literature is relatively recent, and there are few reviews focusing on aspects and methodologies related to airframe design, with the ones of (21) and (33) standing out in this area. In particular, no surveys have been found which have evaluated the overall field of RPA synthesis methods, organising the references in diverse topical areas attending to the characteristics of the design approaches, so as to pinpoint their current status and gaps. Thus, the first goal of the thesis is to conduct such a review, which will serve to inform the choices made at further stages of the doctoral research about the main focus and topical areas to be investigated, as well as to substantiate the formulation of specific objectives within the following ones laid out below.
- **OBJ.2: Performing an assessment on the current status of key topical areas within the broad field of RPAS and exploring their connections with RPA design.** The field of RPAS covers many topics that are currently attracting significant interest in research and development, some of which are also tightly related to area of aircraft design, thus linking with the core topic of the thesis. It can be expected that some of these topics can provide remarkable benefits to current design approaches for RPA, as it will be substantiated later on by the results of the overall state-of-the-art overview conducted in the thesis. Three key areas stand out that will be covered within the thesis work, with each allowing to formulate a specific associated objective. In all cases, it is sought is to evaluate the current status of these areas, exploring their connections with the realm of aircraft design, and providing original insights on their opportunities and challenges towards their integration in RPA design approaches:
 - **OBJ.2.1: Reviewing the current status of RPAS regulations and evaluating their potential integration in RPA design methods.** This topic is relevant both from the perspectives of safety and design, and it represents one of the most dynamic areas in the current field of RPAS as

a whole. For this objective, it is sought to explore the current landscape of RPA regulations and to evaluate their characteristics to assess the possibility of integrating them in design methods.

- **OBJ.2.2: Investigating the field of aircraft computerised design tools to assess their suitability for the design of RPA.** As developed later in the thesis, software environments for the design of manned aircraft are widespread, and a few works have tackled the design of similar tools for RPAS. Considering the challenges and differences in the design of RPA, the purposes here are to evaluate whether the current tools can address the main hurdles towards RPA development, and to propose which characteristics these tools might require so as to achieve the needs demanded by RPA.
- **OBJ.2.3: Explore the potential connections and possibilities of the use of AI in topics related to RPAS design.** The investigation of potential applications of AI in the broad realm of RPAS constitutes one of the most dynamic areas within this field, with the use of AI both in aircraft design and optimisation, as well as in RPAS, being among the most promising areas for the application of these methodologies in aerospace engineering and aviation (64; 65). The purpose here shall be to provide a contextual overview on the use of AI within aviation while paying attention to safety considerations, so as to explore the perspectives, opportunities, and challenges of the use of AI in subject areas related to RPAS design.
- **OBJ.3: Developing novel systematic conceptual design approaches towards the initial sizing of fixed-wing RPA.** This constitutes the paramount goal of the research presented in this thesis. Accomplishing it requires to address the previous ones beforehand, so as to direct the efforts here towards the most relevant topical areas and gaps in the field of RPAS conceptual design. The methodologies to be developed as part of this objective should both be adapted to the particularities of RPA, and seek to aid the designer in the development of aircraft which can leverage the potential of the singularities of these systems, such as their multi-mission nature. Part of this objective includes to establish the scope and main focus of the design methods to be developed here, in view of the results from the state-of-the-art analyses and assessments conducted as part of the previous two objectives. With this, is outlined here that three specific areas of work can be formulated, which shall be distinct parts of an overall initial sizing method resulting from their combined use:
 - **OBJ.3.1: Estimation of new statistical trends for use in RPA design.** Empirical trends constitute one of the main assets within the early stages of aircraft sizing and they can be leveraged in different design approaches

and stages. Since the classic trends for manned aircraft would not be applicable for RPA, new ones have to be derived. This objective includes the compilation of a RPA database from which to extract these trends.

- **OBJ.3.2: Develop novel design-airworthiness integration methods for RPAS.** The purpose is to propose procedures for the systematic extraction of design criteria from airworthiness regulations to integrate them in RPA sizing approaches, while considering the singularities of airworthiness regulations for these aircraft, as seen in the outputs of OBJ.2.1. The regulations reviewed when addressing that objective will also constitute the main corpus of documents considered here.
- **OBJ.3.3: Develop original analysis and synthesis methods for multi-role RPA design.** The purpose is to tackle one of the main gaps in the current landscape of RPA design methods, which contrasts with the marked multi-mission nature of these aircraft. This includes the development of novel performance evaluation tools as well as their integration within a sizing process which can ensure that the aircraft concept complies with all desired operations.

As mentioned beforehand, some of the specific objectives listed above emerge from the findings and results of the research conducted to address previous ones. For instance, the selection of the three key topical areas to be covered within OBJ.2 can only be fully substantiated after conducting an overview of the main topics within the realm of RPA design research. Figure 1-4 showcases the order and connections among the objectives and brings forward in advance how the findings from the research conducted on the first ones influence the specific goals established in the later ones. Considering this, a thorough investigation of the first ones is required to lay solid foundations that will serve to decide which types of design methodologies must be developed within OBJ.3, as well as the key points that these must cover. The findings shown in the figure only constitute an outline, and their full development and discussion shall be developed through the text. Furthermore, the descriptions and substantiation of the objectives as formulated above shall also be enriched with the findings resulting of the analysis on the preceding ones, as it will be seen along the thesis. Finally, it can be seen that the three main objectives configure distinct stages in the research, which will also be seen in the next section describing the contents and structure of the thesis.

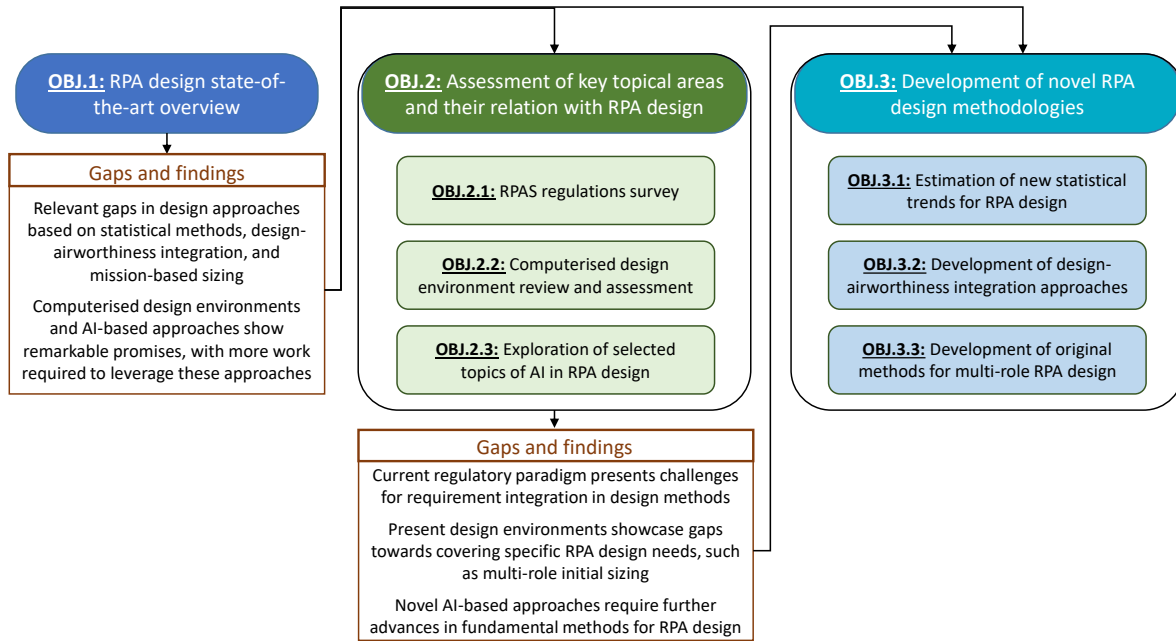


Figure 1-4. Order and connections among the different objectives of the doctoral research, along with an advance of the main associated gaps and findings.

1.5. Thesis contents, organisation and structure

Having established the main objectives of the thesis, it is seen that this research shall cover various topics related to RPA design. Furthermore, the distinct nature of the objectives formulated beforehand leads to different kinds of research efforts, resulting in distinct types of contributions which shall be the main outputs of addressing each of the goals of this investigation. This section outlines the key types of contributions that will result from tackling the objectives, and provides information on the structure and flow of this document.

The main types of research contributions of the thesis, and their relationship with the aforementioned objectives, would be the following:

- RCT.1: Reviews on key areas related to RPA conceptual design.** As mentioned beforehand, most of the literature on RPA design is relatively recent, and up until now there are few reviews covering particular areas related to the main topics of this thesis, specifically the field of synthesis approaches for the first stages of the RPA design process. Furthermore, in other areas which present a larger number of previous reviews, such as the field of RPAS airworthiness regulations, these may have become out of date, considering the extraordinary dynamic nature of these areas. Conducting up-to-date and detailed surveys on topics such as these is essential to avoid the repetition of research work and detect the key gaps to be covered by the research presented in this thesis. Therefore, the findings from these reviews shall serve as foundation for the decisions on the investigation

efforts of the thesis. Furthermore, the objective is not only to use the knowledge compiled here to perform the corresponding gap analyses and to apply the most relevant findings within the conceptual design methodology development stage. Rather, it is also intended that these surveys can be useful on their own as part of the contributions of this thesis, particularly with respect to seeking the curation and organisation of the information found in each of these areas, which can then serve as basis for future work in their specific fields. This type of contribution is related to both OBJ.1 and OBJ.2 of the thesis.

- **RCT.2: Assessment on the current status of key areas related to RPA design and proposal of original insights on opportunities, challenges and future directions.** this type of contribution is tightly related to the previous one, in that a detailed survey is first required to conduct this kind of research effort. For these, the purpose would not be to organise and discuss the current material on a certain subject area, as this would be covered by the above-mentioned review contributions. Rather, the objective is to propose novel ideas and insights on the connection of these areas to the topic of RPA design, and on the main opportunities, challenges, and possible future lines of research. For instance, after performing an analysis on the current status of computerised design environments, it is sought to assess and discuss whether the available tools can cover the challenges of RPA design commented in section 1.3, which is done through a comparison of the capabilities of current software suites with the aforementioned hurdles. This will allow to derive insights on the degree to which present environments can address the design of RPA, and if further work is required, to see which are the most critical areas for future development. The key point here would be that this evaluation effort and the extracted conclusions would constitute original analyses and results from this thesis. The purpose is that these findings then also serve to direct the research efforts of the thesis in terms of development of novel design procedures, and they can also help to underpin future original contributions developed in these areas. This kind of contribution shall be developed for OBJ.2.2 and OBJ.2.3.
- **RCT.3: Novel design methodologies for RPA design.** this is the paramount type of research effort of the thesis, representing novel contributions in terms of systematic design approaches that can be applied in the first stages of RPA design. As mentioned beforehand, the emphasis is not in the design of a specific RPA to develop a pre-defined mission, rather on the development of new design methods themselves, which can then be applied to diverse use cases, each representing the development of a distinct aircraft. The development of these methodologies shall consider the current state-of-the-art status on each of the topical areas of relevance, and will be accompanied by application cases of specific aircraft to validate them. This kind of contribution is related to OBJ.3.1, OBJ.3.2 and OBJ.3.3.

In the same way that the objectives of the thesis are related to each other, these types of contributions are also interrelated. The review efforts serve as basis for the original insights proposed in the various applicable topical areas, and both of them serve as groundwork for many aspects influencing the development of the novel design methodologies. Therefore, even if the main goal of the thesis is represented by OBJ.3 and thus by the third type of contribution listed above, a significant effort shall be carried out within the other kinds of contributions. Not only is this crucial to establish a solid foundation when developing the novel design methods, but it has also been seen that they can contribute added value to the current literature of RPA design, particularly in a relatively new area as is that of aircraft design methodologies for RPA. It is also noted here that the aforementioned three categories are broad types of contributions, and the specific results and conclusions pertaining to each objective shall be developed through the text.

In view of all the above, the overall index of the thesis can be established. A structure is proposed with a first division level in parts, and a second level of partition in chapters. In Figure 1-5, the main schema of organisation of the contents of the thesis is shown. Where applicable, each chapter is related to the objectives that it seeks to cover as well as the types of contributions resulting from the research conducted within. It can be seen that the thesis structure has been organised attending to the aforementioned precedences among objectives and contribution kinds. A brief overview of this structure is provided below:

- **Part I:** it covers the introductory chapter, which serves to contextualise the topic of research, and to establish the scope, objectives, sought contributions, and structure.
- **Part II:** the purpose of this part is to cover both OBJ.1 and OBJ.2 as established in section 1.4. Thereby, the main survey effort of both of the overall field of RPA design is conducted here, which is addressed in chapter 2, as well as that the three key topical areas identified beforehand, resulting in contributions of type RCT.1. Each of the three specific topics is covered in a different chapter, since their scopes and areas of research are notably different. Furthermore, some of these surveys will also be used as a basis for contributions of type RCT.2, proposing novel insights on the current status and future research efforts for these three areas, some of which shall have a direct influence in the development of the novel design methods later on. When considering part II as a whole, it can be considered to represent the overall state-of-the-art analysis of the thesis, also including the main theoretical background on each of these topics.
- **Part III:** having completed the evaluation of the state-of-the-art topics related to RPA design, this part starts in chapter 6 by synthesising the findings from the previous analyses. These shall have a definite influence on the main disciplines considered when developing the novel design methodologies, and also on the

main philosophies when developing these approaches (such as following a modular approach). Thus, this chapter establishes the main objectives for the novel design methods, and introduces the three main lines of research to be developing in the following three chapters, corresponding to each the specific areas of OBJ.3.1, OBJ.3.2 and OBJ.3.3, being statistical approaches, airworthiness-based approaches and performance-based methods, the latter of which includes the consideration of multi-role aspects in the design loop. Finally, chapter 10 wraps up the different lines of design work explaining how they combine to constitute an overall initial sizing method. The contributions in this part are of type RCT.3, constituting the paramount original research results of the thesis.

- **Part IV:** to wrap up this thesis, this part includes an overall discussion on the main findings along the thesis in chapter 11, as well as the global conclusions and proposed future lines of research within chapter 12.

The aforementioned organisation schema has been proposed since, when looking at the thesis only focusing on the four main parts, a classical schema is seen of: **(A)** Introduction; **(B)** Theoretical background and literature Review; **(C)** Materials, methods and results; **(D)** Discussion, conclusion and future work. However, as each of the parts of the thesis tackles very different topics and objectives, they have been divided at a finer granularity level into chapters in order to maintain the focus on a specific topic at a time. It should be noted that, as also seen in Figure 1-5, many of these chapters themselves also present, at a lower level of granularity, the classical sections of organisation of a research work commented beforehand, but applied to their particular area.

Another aspect which can be seen is that the topics covered along the thesis progression first start with broader topics, moving from a study of the broad area of RPA design, on to specific key areas along part II which still have a remarkably extensive scope. Then, when starting part III, firstly the design methodologies are proposed in chapter 6, to then delve into each of them in the following ones. Up until this point, it can be said that a top-down flow has been followed. Then, chapter 10 returns to the level of the combination of the design approaches, and part IV does not only deals with specic discussion and conclusions for each of the topics, but also includes more general remarks. Thereby, it could be said that a bottom-up approach from more specific topics to a broader overview is followed in these last steps of the thesis, even if part IV covers both specific and general aspects. This organisation of the thesis covering at different points broader and more specific topics seeks to provide a more encompassing view of the different topics and approaches related to RPA design, contextualising the specific ones within the broader ones, and also providing a flow of informations and needs from the latter topics to the former ones. This shall be more thoroughly substantiated in view of the findings from the overall survey conducted within chapter 2.

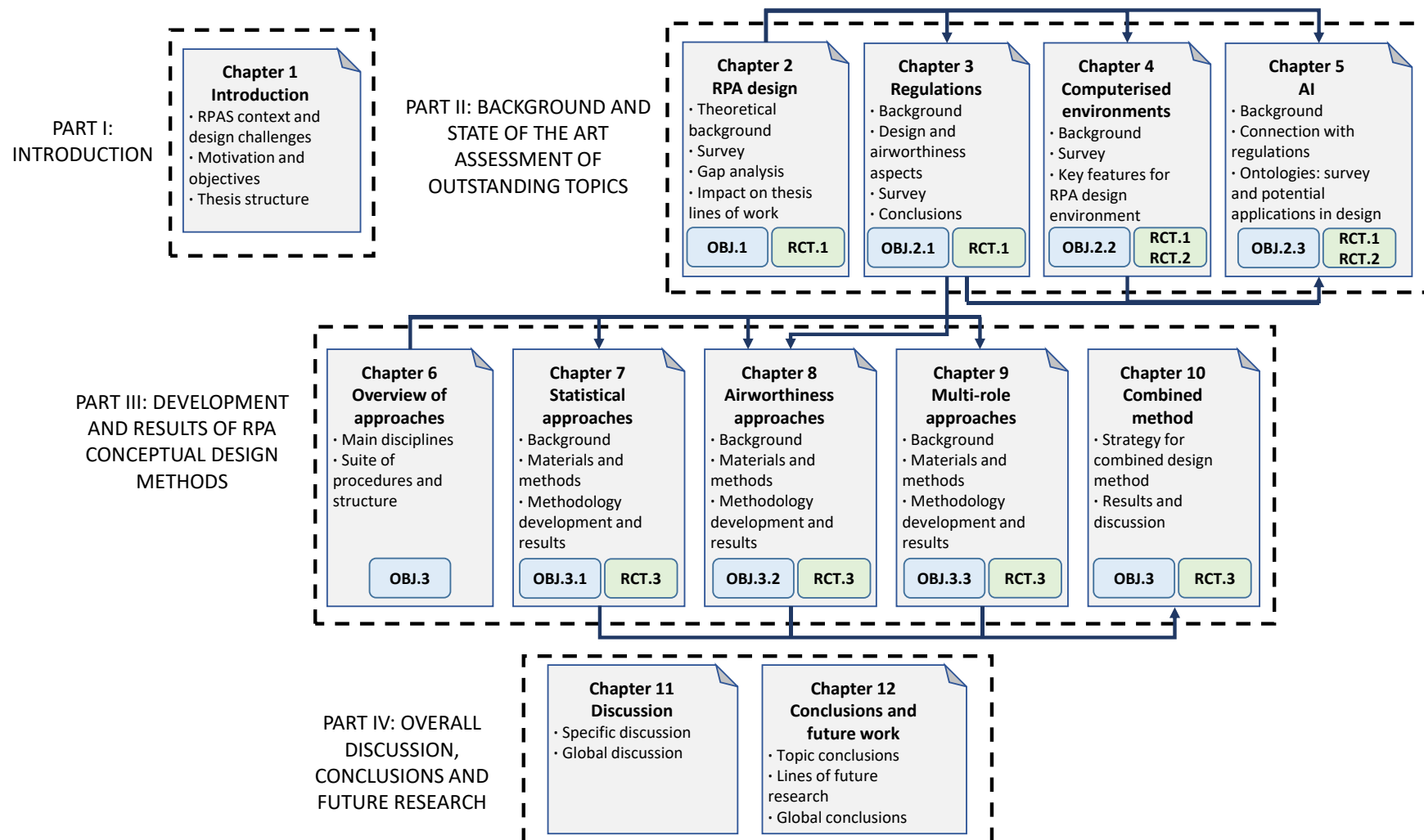


Figure 1-5. Organisation schema of the contents of the thesis.

1.6. Research results and collaborations

Part of the research undertaken for this thesis has been presented and published along the duration of the doctoral studies within journal articles, conference proceedings, and oral presentations. Furthermore, a research collaboration within the UPM and an international research stays have been conducted. This section lists these research results and collaborations and comments their relationship with the contents of the thesis.

The following research stays and collaborations were conducted:

- 1) *Ontology Engineering Group (OEG), Escuela Técnica Superior de Ingenieros Informáticos (ETSIINF), Universidad Politécnica de Madrid (UPM), 2020*: this collaboration within the UPM was invited and supervised by Dr. Asunción Gómez-Pérez, Dr. María Poveda-Villalón, and Dr. Raúl García-Castro. The purpose was to investigate the opportunities and uses of AI-related approaches, particularly the use of ontologies as a knowledge representation paradigm, within the field of aircraft computerised design environments. This topics is related to both chapters 4 and 5 of the thesis, and the findings and results of the collaboration are found within them.
- 2) *Cranfield Safety & Accident Investigation Centre, School of Aerospace, Transport and Manufacturing, Cranfield University, 2023*: this international research stay was invited and supervised by Mr. Cengiz Turkoglu, Senior Lecturer & Course Director. The purpose was to investigate the current international airworthiness regulatory paradigm for RPAS, as well as to develop novel techniques for certification requirement extraction to integrate them in design approaches. These topics are related to both chapters 3 and 8 of the thesis, and the findings and results of the stay are found within them.

The published material from the doctoral research and its relationship with the different chapters is commented below:

- 1) *Gómez-Rodríguez, Á., Sanchez-Carmona, A., García-Hernández, L., Cuerno-Rejado, C., Remotely Piloted Aircraft Systems conceptual design methodology based on factor analysis, Aerospace Science and Technology, 90, 368-387, 2019. DOI: 10.1016/j.ast.2019.04.041*: the paper presents the use of the statistical methodology known as factor analysis on the RPA database which was employed through the work of the thesis. It includes the application of the approach on the database analysing two different case studies, the development of a new rapid sizing method based on the obtained results, and a case study to quantify the accuracy of the sizing method. The contents of this paper are related to chapter 7, particularly to part of section 7.4 and to section 7.6.

- 2) *Gómez-Rodríguez, Á., Sánchez-Carmona, A., García-Hernández, L., Cuerno-Rejado, C., Assessment of aircraft conceptual design tools towards the synthesis of Remotely Piloted Aircraft platforms, EUCASS 2019, 1-4 July 2019, Madrid, Spain. DOI: 10.13009/EUCASS2019-578*: this conference manuscript contains an overview and assessment of computerised design environment for manned and unmanned aeroplanes, focusing on the key features and their trends within state-of-the-art design packages. Furthermore, it conducts an assessment on the required characteristics to develop computerised design environment for RPA design attending to the singularities of these aircraft, proposing insights on future directions in this regard. The contents of this publication are related to chapter 4, particularly to sections 4.5 and 4.6.
- 3) *Gómez-Rodríguez, Á., Poveda-Villalón, M., García-Castro, R., Gómez-Pérez, A., Cuerno-Rejado, C., Towards the Use of Ontologies in Remotely Piloted Aircraft System Conceptual Design: Opportunities and Challenges, AIAA SciTech 2021 Forum, 11-15 and 19-21 January 2021, VIRTUAL EVENT. AIAA PAPER No: AIAA 2021-1061. DOI: 10.2514/6.2021-1061*: this conference contribution is a result of the research collaboration with the OEG of the UPM. It contains a review and assessment on two topics which later intersect: computerised design environments for manned and unmanned aircraft, and ontologies in aircraft design and related areas. The first part expands upon the assessment developed in the previous work. The second examines the existing ontologies in the fields adjacent to aircraft design. In view of the previous analyses, opportunities of using ontologies within aeroplane design environments are proposed. The first part is related to chapter 4, particularly section 4.4, whereas the second is related to chapter 5, particularly section 5.3.
- 4) *Gómez-Rodríguez, Á., Unmanned Aircraft Systems in EASA Regulatory Framework and connections with AI and U-Space, Panel UTM-14: Artificial Intelligence in U-Space, Airspace Integration Week 2023, 25-28 September 2023, Madrid, Spain*: this conference participation was invited by Prof. Rosa María Arnaldo Valdés. The main topic of the contribution are the connections among regulations for design and operations of RPAS with those in the U-space area, as well as the prospective links and opportunities of AI within these areas. This work is related to chapter 5, particularly section 5.2.
- 5) *Gómez-Rodríguez, Á., Turkoglu, C., Cuerno-Rejado, C., A Systematic Approach towards the Integration of Initial Airworthiness Regulatory Requirements in Remotely Piloted Aircraft System Conceptual Design Methodologies, Aerospace, 11(9), 735, 2024. DOI: 10.3390/aerospace11090735*: this paper is a result of the international research stay developed at Cranfield University in 2023. It presents a survey of the current airworthiness regulations in the field of RPAS, as well as a systematic methodology for design criteria extraction towards their integration

in RPAS design methodologies. The contents of this paper are related to chapter 3, which is focused in the review part, and chapter 8, where the design-airworthiness integration approaches are presented.

2. RPA DESIGN THEORETICAL BACKGROUND AND STATE OF THE ART

This chapter has two main goals. The first one is to introduce the main theoretical background of the topic which constitutes the backbone of this doctoral thesis: RPA conceptual design. This discipline can be considered as a subset of a wider area, which is that of aircraft design. Thereby, section 2.1 provides an overview of the main principles of this subject, its main phases, and the definition of specific concepts which are tightly related to the research presented in this thesis. As mentioned in chapter 1, aircraft design is a multidisciplinary endeavour. The focus in this section is placed on the general aspects of design, whereas other chapters shall place more emphasis on particular disciplines and paradigms, but always within the overall context introduced in the present chapter.

The second main purpose of this chapter is to provide an overview of the state-of-the-art open literature on RPA design, so as to cover OBJ.1 of this research. Since this field is very broad, a high-level evaluation of several subjects and areas of interest tackled in previous works shall be conducted here. This analysis also allows to identify key topics where research gaps are present. The findings from this broad overview of the current literature on RPA design serve as the main guidance to direct the efforts of the investigation conducted within the doctoral studies towards specific research areas which shall be the focus of the following chapters, thus having a paramount influence on the other objectives of this investigation and on the main research contributions to be developed in the thesis.

In summary, this chapter provides the main foundational theoretical ground and high-level state-of-the-art analysis on which the rest of the surveys, assessments, analyses, and methods of this thesis are further built upon, each within its particular context.

2.1. Aircraft design theoretical background

From a broad perspective, the notion of “design” as a noun, as given by Gudmundsson, is the following: *“A design is a pattern of geometrical, physical or mathematical features that is the consequence of an intent and purpose. A design requires an originator who intended for the pattern to look a certain way so it could serve its proposed purpose. This way, a design is a subset of regular patterns and one that has a preconceived goal, requires planned actions to prepare, and serves a specific purpose”* (9). From here, it could be said that the concept of “design” as a verb (such as in “to design something”), would be the process of “planned actions” commented in Gudmundsson’s definition, which, when followed, allows the originator (or designer) to arrive at a formal definition of the features which describe the concept that is being sought in this process.

Moving on to the particular field of aircraft design, by application of the previous definition, here, that which is being sought to be designed would be an aircraft, and the

aircraft designer would be its originator. An aircraft can be defined by many features at different levels of granularity and detail. Some examples of these features, at a broad level of definition, can be geometrical properties (such as wingspan, wing surface, horizontal tail surface, fuselage length, etc.) and mass properties (such as design masses as the Maximum Take-Off Mass), amongst many others. Therefore, the objective of the aircraft designer is to estimate the values of these features so that the aircraft can serve its intended purpose. This purpose is usually formalised as a set of initial requirements, which are available prior to the design of the aircraft. The nature of these specifications can be varied, and they usually include performance objectives (such as endurance or range with a certain payload) and airworthiness considerations as two of their main dimensions.

The aircraft design process can be considered as the set of activities which start from the initial requirements with which the aircraft must comply, and through the application of a series of methodologies, it reaches as an output the manufacturing blueprints for an aircraft which complies with the intended specifications stated at the start of the process (7; 9). Aircraft design is a complex, multi-stage endeavour in which many different aeronautical analysis disciplines intertwine (aerodynamics, performance, structures, propulsion, etc.). During this process, the aircraft to be designed is progressively defined and refined following an incremental approach, starting by estimating a set of key variable and mass properties within the initial sizing steps (8; 12), moving on to a larger set of variables which provide a rough geometric definition of its Outer Mold Line (OML) (8; 10), and finally arriving at a complete definition of the properties of each component and the system as a whole (11; 51). It can be considered that this progressive evolution of the aircraft definition represents a continuous increase in its Technology Readiness Level (TRL) (11).

In the context of this thesis, a design methodology or method is considered as any set of steps which aid the designer either in either:

- Making qualitative decisions which affect the outcome of the aircraft that is being designed (for instance, the selection of the tail configuration or engine type).
- Estimating or refining the values which define relevant features of the design in a quantitative manner (for instance, selecting a wing loading which complies with all applicable performance limitations).

As mentioned in the introduction, the main objective of this thesis is the development of novel design methodologies for RPA, particularly for their initial design stages. Therefore, the purpose is to develop systematic methods that aid the designer in this process of design, so as to reach designs that fulfil their intended purpose as established in their initial requirements.

Having seen the main definitions applicable to the context of design in this thesis, in the following, this section seeks to provide the essential information to contextualise the research efforts presented in this thesis within the discipline of aircraft design, and to make this document more self-contained. A detailed development on the philosophy and purpose of aircraft design, its relevance within the aviation industry, and many other topics pertaining to this discipline, are available in many recognised texts on this subject, including but not limited to (7; 8; 9; 11; 14; 16; 48; 51; 66). These books, complemented with others which are specifically focused on the design of RPA (6; 10; 13; 67) have been the main references that have served as support when writing this part of the thesis.

2.1.1. Analysis and synthesis approaches

Two fundamental concepts in the field of aircraft design are those of analysis and synthesis. Both kinds of approaches are commented herein.

In broad strokes, an analysis approach can be considered as a methodology which, from a definition of an aircraft (which typically includes its geometric and physical characteristics up to a certain level of detail), seeks to obtain its performance and behaviour (such as its integral and point performances, or stability and control characteristics, amongst other possibilities). Therefore, the input data are the features of an aircraft (design) that is already defined – at least to a certain extent -, and the objective is to analyse its behaviour. An example question when following an analysis approach may be: “what range can this aircraft achieve when carrying this payload?”, or “what are the landing distances of the aircraft in different loading and altitude conditions?”.

In contrast, a synthesis approach follows the reverse process. The inputs are a set of requirements with which an aircraft must comply. In this case, the aircraft is yet to be designed, or it could already be defined up to a certain extent but it is sought to refine and extend its conceptualisation. By applying a synthesis approach, which is a creative process, the outputs are the definition of the aircraft which satisfies the aforementioned requirements (51), that is, its geometric and mass properties, among other possibilities. An example question when following a synthesis approach could be: “what would be the required design masses of an aircraft to allow it to fly this route with a certain range, cruise speed and altitude?”, or “what would be the wing loading required of an aircraft that would allow it to land in a established field length and height?”. The scope of both analysis and synthesis approaches can either be focused on a single discipline (performance, aerodynamics, structures, etc.), or rather it can be determined by a combination of subject matters. An illustration of these two concepts is shown in Figure 2-1.

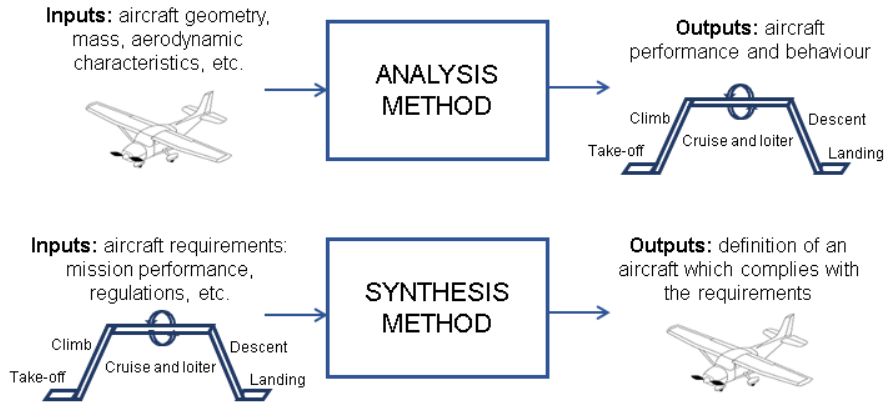


Figure 2-1. Illustration of the concepts of analysis and synthesis approaches.

Albeit analysis and synthesis represent different perspectives, in reality both concepts and approaches are tightly interrelated. Given a particular discipline (for instance, performance), both analysis and synthesis approaches are governed by the same fundamental laws and mathematical relationships. In an analysis performance calculation, knowing the initial and final weights of a cruise flight, as well as the speed, aerodynamic efficiency and specific fuel consumption; by using the simplified Bréguet equation for jet aircraft [[2-1], used here as an example, the range of the cruise segment can be computed. However, by using the same mathematical expression but solving for the weight fraction, and knowing instead the desired range, a synthesis approach can be undertaken, as is done in many design manuals (7; 8; 11).

$$R = \frac{V}{C_{jm} g} \frac{C_L}{C_D} \ln \frac{W_i}{W_f} \quad [2-1]$$

$$\frac{W_i}{W_f} = e^{\left[\frac{R C_{jm} g}{V \frac{C_L}{C_D}} \right]} \quad [2-2]$$

Where R represents the range, V the true airspeed, C_L/C_D the cruise aerodynamic efficiency, C_{jm} the specific fuel consumption as defined per fuel mass flow and per unit thrust, g the acceleration of gravity, and W_i and W_f the initial and final weights of the flight segment.

This simplified example showcases that, in spite of being two distinct approaches, the fundamental disciplines governing them have the same physical-mathematical basis. It is true, however, that generally synthesis (design) problems have many more degrees of freedom than analysis approaches. This is because the main inputs for synthesis are, for the most part, the initial requirements, and much of the aircraft data at this point is unknown, as it will be progressively defined along the stages of the design process. This is a recognised challenge in aircraft design, thus usually in the first phases of design many assumptions have to be made in order to arrive at closed-form equations. Thereby, the use of data from similar aircraft, statistical methodologies or assumptions which simplify

the problem are the norm in these early stages of design (11; 51), and sound reasoning from the designer is fundamental towards arriving at adequate solutions (10).

Going forward in this thesis, another relevant idea linked to these concepts is that, considering a particular discipline, the applicability range of both analysis and synthesis approaches is decisively influenced by the underlying hypotheses employed when deriving the physical-mathematical model to be employed. When developing these methods, these hypotheses are selected attending to the aircraft type, the mission type, the flight conditions, etc., and overall they set the scope of the model. It is generally recommended to employ these models only for analysis conditions and aircraft types according to the scope with which they have been derived (6; 11; 50). As brought forward in the introduction, several challenges in RPA design need the revision of classical hypotheses employed in manned aircraft design, as well as the derivation of new models, in order to ensure their applicability within this field. One of the main objectives of this research is to tackle these challenges and develop new approaches for RPA conceptual design that give an answer to them. Thereby, in some points along this thesis, new synthesis approaches will not be able to be directly derived from existing analysis models, as they do not cover some of the capabilities that are sought in this research. In these cases, novel analysis methodologies might have to be derived in the first place, so as to then develop a synthesis approach which leverages them in order to conduct the initial sizing of RPA according to their particular principles. As an illustrative example, current simplified integral performance analysis approaches do not consider the flexibility in flight profile and flight laws that would be required for multi-role RPA. Thereby, in chapter 9, firstly a new performance analysis method is developed, and at the next step, a synthesis approach which uses this approach is conceptualised.

2.1.2. Phases of the design process and their usual methodologies

As mentioned beforehand, the aircraft design process is a complex undertaking which, starting from a set of initial requirements and a clean sheet, must arrive at the final manufacturing blueprints of the aircraft, with a full characterisation of all its components. In order to tackle this task in a rational and systematic manner, the design process is usually divided in different stages, seeking a gradual evolution of the aircraft concept from a basic definition to the full level of detail required at the end.

Within the open literature, there are many different notions and approaches to divide the aircraft design process in distinct stages (7; 8; 10; 11). In broad terms, different design stages can be characterised by aspects such as the level of knowledge on the aircraft concept at each point along the design continuum, the type of analysis methodologies employed within each phase, the level of fidelity that is sought, the inputs to the design stage as well as its envisioned outputs, the aircraft design disciplines considered, and the level of detail of physical phenomena which are taken into account. Most of these dimensions are interrelated, as it will be discussed below. For instance, analysis

methodologies with a high level of fidelity can typically only be used when the level of knowledge of the aircraft is already relatively developed, thus complicating their application in earlier stages.

It is key to establish at this point the model of the design process used through this research, including the definition of the different design stages. These aspects have an outstanding influence on the analyses and discussions developed through the rest of the text. For instance, the classification of previous RPA design works according to topical areas, as it will be seen within the survey to be conducted in section 2.2, will use as one of the main categorisation criteria the design phase to which each type of method would belong. Furthermore, the original design methodologies to be developed within part III of the thesis are focused on the conceptual design stage, according to the overall scope of this dissertation, so it is key to lay out in advance what are the main characteristics of this stage as considered in this research. This is particularly significant, as different references in the field can often follow very distinct design process organisation schemas, with dissimilar definitions of the various design stages, in such a way that what is considered conceptual design according to one source might fall in the preliminary design stage attending to the criteria of another work. Thereby, this subsection provides a description on the schema of the design process organisation which is employed through the thesis.

(a) Schema of design process stages used in this thesis

The design process schema which is used in this thesis is based on the classification and definitions provided in authoritative design texts such as those of (7; 8; 11), which separate the full process in conceptual, preliminary and detailed design. This outline is also employed in recent aircraft design manuals, both from the field of manned aircraft design (9; 14; 51) and those dealing in particular with RPA design (1; 10; 13), and this schema is also followed in recent research (12; 49; 50; 62; 63; 68). Table 2-1 represents a summary of the main characteristics of each design stage, which are further developed in the text below.

Table 2-1. Summary of main characteristics of the three aircraft design phases. Information has been mainly obtained from (11), with some modifications.

	Conceptual design	Preliminary design	Detailed design
Main objective	Starting from initial requirements, arrive at a first definition of the overall aircraft	Refine the conceptual estimations with higher fidelity and considering more disciplines simultaneously	Arrive at the final manufacturing blueprints of the aeroplane
Inputs	Initial requirements	Result from conceptual design	Result from preliminary design
Main outputs	Initial baseline design. General arrangement, basic dimensions, main design masses	Basic internal arrangement and complete external configuration	Detailed definition of each component and overall aircraft
Design space breadth	Broad	Intermediate	Reduced

	Conceptual design	Preliminary design	Detailed design
Level of aircraft definition	Low (TRL 2-3)	Medium (TRL 4-5)	High (TRL 6-7)
Methodologies employed	Rapid estimation methodologies, usually statistical relationships and simplified physical models	Multidisciplinary Design Optimisation (MDO) approaches	Detailed high-fidelity simulations and exact Computer Aided Design (CAD) geometric representation
Example disciplines	Aerodynamics, initial mass estimation, performance, costs	Loads, refined mass estimations, stability and control, structural analysis and design, aeroelasticity, systems design	Systems design, detailed geometric definition, mass allocation and measurement, manufacturing
	Airworthiness and certification		
Cumulative cost committed^a	Over 80%	Over 90%	Close to 100%
Acceptable margin of error	10-15%	1-5%	As low as possible

a: this concept does not represent the cost dedicated to carrying out the phase, rather, it represents the cumulative percentage of the whole life-cycle cost of the project which is affected by the decisions taken along the progression of the design stages.

As it can be seen, the objectives, methods and characteristics of the three phases are starkly different. However, they all fit, within the timeline of the design process, with the particularities required at the different stages of aircraft definition and development.

(a.1) Broad trends affecting the overall design continuum

Before delving in some particular aspects of each of the three design phases, firstly some broad trends affecting all of them shall be commented. In particular, there is a tight relationship among the following characteristics:

- Design space breadth.
- Level of aircraft definition.
- Complexity and fidelity of the employed methodologies.

The relationship among them is governed by the general idea of progressive refinement and convergence of the design along the sequential stages of the process. This is a key philosophy in the aircraft design process (10; 17; 51), and it is also a cornerstone viewpoint of the National Aeronautics and Space Administration (NASA) Systems Engineering Handbook (69).

In the first steps of the development process, the design space is very broad, as no aspects of the aircraft, or only a few of them, have yet been defined at this point. Thereby, there are a multiplicity of design solutions and combinations of values of different variables that could be considered. However, not all of them result in feasible or efficient designs.

Therefore, the objective in this stage is to perform a rapid exploration of the broad design space to develop an initial definition of one or various candidate aircraft configurations (19). The methodologies used are simple in nature, and albeit they have a lower fidelity than their counterparts from further design stages, their strength is twofold: first, they have fast calculation times; and second, they are capable of performing initial estimations with few input data (17; 51). This allows to explore the expansive design space quickly at this stage (17), analysing and comparing various concepts to select the ones yielding the best initial estimates (70), and to hone in the design on regions of the design space which are promising regarding the feasibility of the designs.

The usefulness of rapid calculation methods has been emphasised by previous authors, who have highlighted their merit in providing suitable results with low computational efforts (17; 35; 51; 60; 70), which can then be used as baseline and initial points for the higher fidelity methods of later phases. If more sophisticated methods were to be used here, the first issue would be that the computational cost would be unmanageable. The level of fidelity of a model can be understood as how well it represents the actual physical behaviour of the entity or phenomena being studied, and in many cases it correlates with the required computing time for a given set of computational resources (17). Three divisions can be established attending to the order of magnitude of computational time: low fidelity methods obtain results in seconds, medium fidelity ones in minutes, and high-fidelity approaches in hours or days (17). High-fidelity methods are extraordinarily useful when seeking very accurate results for a small set of variations in the aircraft concept (70), but their use at this point in the design process would be hindered as they would have to be applied in many combinations of variables and distinct alternative configurations which represent possible points in this phase (10; 70), with the computational time adding up. In contrast, lower fidelity tools give results of a sufficient accuracy to perform informed decisions at these early phases, so they constitute a promising alternative here (70).

A second issue would be that high-fidelity methodologies usually require a more detailed definition of the aircraft in order to perform their calculations (51). For instance, whereas in the first stages an estimation of the Operating Empty Mass (OEM) via a correlation can be conducted; within the later ones, quasi-analytical methods are typically employed, and they require the geometry of the internal structure layout in order to estimate its mass. The input data required in this latter case is typically not available until the preliminary design stage (11; 12; 51). Therefore, in spite of recent computational advancements, the second issue would remain, as high-fidelity analyses require detailed inputs which are not available until further design phases have been reached (51). These are among the main reasons for the continued use and relevance of conceptual design approaches, as they allow to adequately manage and balance the accuracy of the results with the time and resources invested in the design at this stage (70).

The aspects mentioned above are also the reason why higher fidelity approaches are required within more advanced design stages, as they closely match the needs of these further steps. It is clear that the lower accuracy from low fidelity methods is not enough to achieve a comprehensive design. Thereby, once the design space has been delimited to a smaller region surrounding the candidate configurations selected in the previous stage, higher fidelity methods can be employed. Now, since the breadth of the design space being covered has been greatly reduced to only the most promising areas, the combined computational cost of the set of simulations becomes manageable. More importantly, because the level of definition of the aircraft has increased as a result of the outputs from previous design phases, these methods have the required foundation in order to exploit their capabilities and continue increasing the level of detail of the design (51). It should be noted that the information grows exponentially along the different design stages, with perhaps only tens of variables constituting a broad representation of the aircraft in the first stages, but then reaching hundreds in further stages (10).

Another relevant reason to emphasise the use of high-fidelity methods on the later design stages is that these approaches usually capture phenomena related to geometry definition (such as component unions), as well as other features, which are usually neglected in rapid estimation models. In contrast, these later ones usually focus on higher order effects and neglect the more specific phenomena, which is one of the reasons allowing their computational efficiency. For instance, an aerodynamic semi-empirical model captures well the effects from changes to wing planform geometry, aerodynamic profile and flight regime. In contrast, the additional drag caused by small gaps, protuberances, fillets, excrescences, etc., are difficult to capture with simple formulations, albeit it is possible to employ generalised corrections in lower fidelity models to account for these effects in a conservative manner (9; 54). In contrast, a CFD approach where all nuances of the geometry are captured in the representation can calculate the aforementioned effects accurately. Coincidentally, these sort of geometric details are not defined at a conceptual level, where the level of detail of the design is low, so even if a CFD code were used here, its full potential and advantages could not be leveraged at this point.

The evolution of the design definition also influences the disciplines that are integrated at different stages of the process. As seen in the previous example with the OEM, the same discipline usually has many different analysis methodologies with diverse levels of fidelity. In the case of mass estimation, statistical regressions are used in the first stages, whereas the approaches employed in later ones include quasi-analytical methods, and then to direct mass measurement of components, are employed (10; 11). On the side of aerodynamic approaches, semi-empirical methods commonly employed for conceptual design then leave room in preliminary design for vortex or doublet lattice methods, and then to CFD at the late preliminary and detailed design stages (19; 63; 71; 72). This leads to some authors to present the design process as a spiral, where the same subject matter is employed at different levels of fidelity along the design process, leading to convergence of the design (10; 66; 69). However, not all disciplines can be readily considered from the

early phases of design. This is precisely due to their methods needing a larger volume of input data which is not available from early on. For instance, aeroelastic analyses require both a relatively detailed definition of the aerodynamic surface in order to obtain its loads with accuracy, and also of its internal structure, to estimate mass and inertia properties. As brought forward above and as it will be commented further along the text, details on the internal structure usually remain undefined in the early stages of conceptual design and are only sized later on (11; 12; 73). Other disciplines such as flight control design are also typically addressed later on in the design continuum (12). Thereby, it is acknowledged that there are certain disciplinary gaps that cannot be easily covered until later stages (10; 71; 72). There is a particular case, as observed in the table, which is the discipline of airworthiness, as it appears in relation to all design stages. This is motivated by the different ways in which airworthiness and certification requirements can be integrated depending on the design stage and the disciplines that are considered. As the design definition evolves, more airworthiness aspects related to different aircraft elements and disciplines of analysis can be taken into account. Classic design references such as (9; 48) emphasise the relevance of considering airworthiness considerations from early on within the design continuum. This allows to ensure that, from its first stages of definition, the design concept complies with essential safety requirements. This is intended to avoid the costly redesigns that would result if at a later point, it is seen that certain certification constraints are not complied with. A more detailed exposition on the particularities of airworthiness criteria integration in design shall be developed within chapter 8.

Thereby, it is acknowledged that the combined use of rapid estimation methodologies to explore the initially large space of feasible designs, followed by the application of optimisation and higher fidelity approaches to refine the aircraft definition once a baseline concept has been established, results in a design schema which allows to leverage the advantages of each type of methodology at the proper time during the design continuum (17; 51). This classic gradual approach to design is still considered in recent research works and design processes, where the different objectives, deliverables, and levels of detail of the distinct approaches used in each design stage are acknowledged (51; 69; 74; 75). As a matter of fact, the concept of employing the right level of fidelity at the proper time in the design process links with the notion of multi-fidelity approaches, which is one of the current trends in aircraft design, as it will be expounded later on in subsection 4.4.5.

(a.2) Particular characteristics of each design phase

Having outlined above the general trends that affect the different phases along the continuum, in the following lines, a brief discussion regarding each particular design stage is expounded.

The **conceptual design** stage starts from a clean sheet, and seeks to obtain an initial characterisation of the aircraft which serves as a starting point for future design phases.

The fact that this phase does not start from a predefined aircraft definition is one of its main differentiating features from other phases. The objective is precisely to develop an initial concept, starting from the initial requirements. Reference data of already-existing aircraft which have similar specifications to the one that is being designed, often called similar aircraft, can also be used to support this process and serve as touchstone for the decisions made by the designer and the initial results obtained (76).

This phase is characterised by a significant use of statistical methodologies since, as commented in subsection 2.1.1, the first stages of synthesis have a large level of design freedom. Thereby, using typical values or empirical relationships, both extracted from aircraft of a similar type (8; 76), it is possible to delimit the design space while using as a starting point values extracted from proven designs (51). Simplified physical-mathematical models of certain disciplines are also employed to perform an initial estimation of key variables. A typical task conducted at the conceptual design phase is the selection of the configuration layout, which seeks to study and select the most promising general arrangement (7; 9; 76). This includes aspects such as the positioning of aerodynamic surfaces and the decision on the tail configuration. There are many different methods to conduct this type of analysis, one of which consists in conducting the sizing procedure separately for different candidate configurations, so as to then select the one which yields most favourable results. Therefore, the rapid calculation approaches used in conceptual design should be flexible enough to account to this configuration variability (9; 70). In some cases, various layouts may yield similar results, which might indicate that they are all plausible candidates to consider in further design phases (9; 43), where higher fidelity methods may allow to single out the final decision on general arrangement.

One of the most relevant lines of work at this point is the analysis of the design drivers, which can be considered as the requirements which have the largest impact on the resulting design at the conceptual stage (10). For example, a mission with a large payload requirement could have a significant effect in the structural weight, or a requirement establishing a high climb rate even with a fixed landing gear might result in a significantly increased power from the engine. The rapid calculation methods available in the conceptual design stage allow to conduct requirement analyses at a point in the design continuum where major changes to the layout and geometry, and even negotiations with the entity proposing the requirements, can still be conducted (11; 68). The evaluation of initial requirements and their feasibility is considered as one of the most important steps in aircraft design (11; 49; 66), as certain sets of requirements could lead to non-converging design processes (77).

As seen in Table 2-1, the main output from the conceptual design stage is usually an estimation of the most relevant masses of the overall aircraft, such as the OEM and MTOM, and also its basic dimensions, including the essential variables describing the fundamental components such as fuselage, wing and tail surfaces. A complete external configuration definition usually cannot be achieved at this point (11), but key parameters

such as the span, the surface area, taper ratio and aspect ratio, of the main aerodynamic surfaces would be required as outputs from this stage, with the resulting aircraft concept being defined by approximately several tenths of parameters (10). The output of the conceptual design phase is often called the “*initial baseline design*” (7), which serves as the starting point for further steps. It is also key that an initial performance estimation of this concept is conducted, along with other estimations that allow to verify the compliance of the baseline design with the initial requirements which can be evaluated at this stage. Finally, it is also noted that in some design workflows, the conceptual design phase is further subdivided in different steps (8; 11; 51). These may be grouped in two processes (8): initial sizing, also called at times the “*preliminary sizing*” (8), and preliminary configuration refinement. The first of these seeks to arrive at a first estimation of the main mass and geometry variables starting from the requirements (8; 19). It has been noted that the output of this stage is often not yet at the point where a representative Computer Aided Design (CAD) model of the OML can be generated, as specific details, such as the nose and rear-end geometry of the fuselage, are still to be defined (12). This starting definition is then used by the following preliminary configuration refinement step as a baseline to perform additional modifications and verifications of requirement compliance, with the objective of arriving at a refined definition of the main aircraft components, including at this point an initial OML definition (8). Both of these processes were illustrated in Figure 1-1 at the onset of the thesis, with the focus of this research being particularly in the initial sizing step.

Preliminary design sees a change of focus both in the methodologies employed as well as in the organisational aspects of the design process. Here, there is a shift towards disciplinary analyses performed by dedicated groups of specialists, in contrast to the more generalist approach employed in conceptual design (10; 66). Having already defined many aspects of the aircraft at the conceptual design, a higher level of definition of the aircraft concept with a larger volume of parameters to characterise it can be reached through the use of more sophisticated design methodologies. One of the main objectives of this phase is the sizing of the internal structure of the aircraft (12), which in turn allows to check the weight estimations conducted at the initial sizing stage, using here “bottom-up” approaches that use the dimensions of the structural components to estimate their weight (9; 11). These approaches have more accuracy than the statistical estimations which are preferred in the conceptual stage (50). Other disciplines are integrated at this point of the design continuum, which are typically those that require a higher level of definition of the aircraft, such as stability, control, and aeroelasticity (9; 11). A remarkable aspect is the incorporation of tasks related to systems design (51), which are usually conducted through a systems engineering approach. The design of systems such as the hydraulic, electrical, flight control, and landing gear systems, among others, is usually tackled after the concept phase (51; 63; 78), and once the overall layout has been generated according to the top-level aircraft requirements. At this point, derived requirements for the design of the airframe systems can be allocated (79), and since an initial layout and OML of the aircraft is already available, the internal available space for

systems can also be known and managed at this point, allowing to address key decisions on systems engineering (10; 51). The definition of the systems architecture also opens up other disciplinary studies, such as systems safety assessment analyses and reliability analyses, which usually require as an input the systems architecture and the reliability characteristics of components to evaluate the compliance with safety objectives for different failure conditions (80).

Another distinguishing feature of the preliminary design phase is the shift towards the use of Multidisciplinary Design Optimisation (MDO) methodologies, in order to simultaneously consider the multiple subject areas that are taken into account here (51) (41). Thus, the emphasis is more on analysis than on synthesis, but still following a design workflow, since the geometry is refined and optimised according to the results from these calculations (10). Optimisation algorithms aid in conducting this process of geometry modification and evaluation in a systematic manner (61).

The mathematical models used for various disciplines tend to be of higher fidelity than those used in conceptual design, leveraging the higher knowledge of the aircraft which is available in this stage. Use of CFD and Finite Element Method (FEM) analyses can also be employed at this stage (51), providing valuable insight on more complex phenomena which is not modelled through the rapid approaches used in conceptual design. However, it has been highlighted that the preparation of the inputs for these techniques (such as geometry meshing) is far from automated, requiring a significant processing effort (73), which is added to the higher run-time required by these analyses and the interpretation work after obtaining their results, thus augmenting the time required to evaluate each concept in the preliminary design stage (10). This limits the possibility of employing these techniques on an expansive design space (10), which is one of the reasons why the conceptual design phase previously performs a rapid evaluation of a large design space so as to keep only the most promising configurations for the preliminary stage. In general, it is acknowledged that, once the preliminary design phase starts, modifications to the overall configuration shall be comparatively minor (11), as the extensive design space exploration was already carried out in the conceptual step.

When the **detailed design** stage starts, many aspects of the design are already frozen (51), which means that the efforts here are more localised in particular aspects of the design. High-fidelity methodologies such as CFD and FEM are thoroughly employed to make the final adjustments to both outside and internal layout, including fillets, joints, fittings and attachments (11). Some of the tasks conducted during this phase include the analysis of compliance of local strength requirements (11); the detailed structural, mechanical, and electronics design (9; 11); the accurate layout of systems components such as hydraulic lines (11); and the design of tooling for manufacturing (9). One major defining aspect is that the design is now formalised by an accurate and detailed CAD representation. All of the variables employed in this CAD of the aircraft are part of the design definition, and this complete CAD model is often employed to generate the inputs

for the use of the aforementioned CFD and FEM methods (10). The CAD definition includes both external and internal elements and geometries, since the final output of this phase are the shop designs describing a completely specified product which can be manufactured and ultimately flown (9; 10; 11).

(a.3) Impact and relevance of the conceptual design stage

As it can be seen, the different types of design methodologies, with their respective levels of fidelity, are all critical towards an ordered and rational design process. In particular, as previous authors have stated, in spite of computational advancements in the past years, the conceptual stage and the use of rapid sizing methodologies to perform the initial design space exploration remains a fundamental part of the design process (17), and many parts of this endeavour are still carried out with significant input from the designer (10). The usefulness of the rapid methodologies employed at this stage has been highlighted (17; 35; 70), and in spite of the continued use of simplified approaches herein, the conceptual design phase is acknowledged in both classic (7; 11) and recent works (17; 60; 62; 70) as a crucial step in the overall design process. One of the main reasons for this, as seen in Table 2-1, is the high level of costs compromised with the decisions made here (11; 12). This concept does not represent the cost dedicated to carrying out each phase. Rather, it represents that the decisions taken at a certain design phase have an impact on the costs to be incurred in future ones. For example, if adequate decisions are taken during the conceptual design phase that increase the aerodynamic efficiency of the aircraft, this will mean that it shall consume less fuel during operation, therefore the operation costs have been affected significantly due to arrangements made in a much earlier stage of the aircraft project. This means that the decisions made during the conceptual design stage, even though relatively affordable due to the simplicity of the methodologies employed, have a remarkable impact on the whole life-cycle costs of the aeroplane. Furthermore, modifications to the design at this point, where the design space is still open and the configuration has not yet been frozen, are much more manageable than if they were decided at later stages (19), where costly redesigns might results. The outstanding impact that the conceptual design stage has in the final design results and its viability constitute an incentive towards researching and improving the methodologies employed in this stage of design.

(b) Other design process organisation schemas

As mentioned beforehand, varying notions regarding the design process and its stages can be found within the open literature. An overview is provided of some other concepts and trends which tie with the one which will be used in the thesis.

Due to its tight relationship with aircraft design activities, the systems engineering approach ought to be commented here. This approach is employed in many areas of engineering, and it consists in a structured approach which uses as a basis a hierarchical structure of the system of study, decomposing it into different subsystems at different

levels of granularity, until reaching the component level. The requirements of the overall system are allocated to the different subsystems following the aforementioned hierarchical decomposition, allowing to conduct the design of each element. Then, the integration of elements and subsystems as well as the verification of the requirements at each of the levels of the system decomposition is carried out, until arriving once again at the overall system level. This process is often illustrated in the form of a V-shaped schema, with the decomposition and allocation tasks representing the left side of the letter, and the integration and verification the right side. More details on this subject can be found in references (78; 79).

As mentioned beforehand, systems design and modelling are often considered as one of the disciplines within aircraft design processes. It is usually considered within the preliminary design stage (10) and after the concept phase (78), as according to references both belonging to the aircraft design and systems engineering fields. In the systems engineering field, it is even considered that the aircraft sizing process, which is performed using top-level system requirements, is a previous step to the definition of the systems architecture and the allocation of derived requirements to the distinct subsystems (79). Thereby, there is a strong connection between the disciplines of aircraft design and systems engineering. In the case of this thesis, since it is focused on the conceptual design stage, aspects related to systems design would fall outside the scope of this research, as it was mentioned above that these aspects are usually considered later on along the design continuum, particularly from the preliminary design stage onward.

With respect to the division of the design continuum in the conceptual, preliminary and detailed design phases, albeit the schema and notions presented beforehand are relatively widespread in the field of aircraft design, different criteria and characteristics can be found in the open literature in relation to these stages, their organisation, and the kind of methodologies employed in each of them. It should be noted that classic references following the design process schema which is used in this thesis have highlighted that the tasks and methods of distinct design phases can often overlap, and the order might be changed depending on the designer's perspective (7; 9). This may be one of the reasons for the distinct approaches to the design continuum followed in other works. In particular, some authors emphasise that current trends in the field of aircraft design could blur the classic divisions among stages, such as tasks pertaining to the conceptual and preliminary stages becoming increasingly merged (10), or higher fidelity methods typical of the detailed design stage being employed within preliminary design, for instance through the use of subrogate modelling to alleviate the computational effort (81). These trends are presently still being explored within the state-of-the-art, and they will be discussed in more detail within subsection 4.4.5.

2.1.3. Generic Design Methods (GDM) and Ad-hoc Developed Design Methods (AADM)

Upon reviewing the RPA design open literature, and also concerning the wider aeroplane design area, two distinct types of works were identified attending to the ways in which design methodologies are developed and used. In this section, a comparison is made between these two approaches. This classification shall also be one of the focal points of the literature review to be conducted in section 2.2.

The first of these kinds of works propose design methodologies that are usually given employing a generic formulation, and which are presented with a broad applicability scope. This implies that these have not been developed with a particular design case study in mind. Rather, they can be applied to different sets of initial requirements, and following the steps described within the methodology, a different output aircraft would be obtained in each case. A classic example would be Roskam's preliminary sizing method given in (8). This method can be applied, with a few adaptations such as changing the reference values and regressions employed, to different kinds of aeroplanes (from transport to fighters), and depending on the inputs given by the user and the criteria employed, the outputs are different in each case. Many design manual methods follow this approach (7; 10; 48; 51), as the purpose of the authors is for the methods to be generic and can thus they can be applied to a variety of particular cases, within the scope considered when devising the design method. If case studies or examples of application are given, they are mainly for illustrative purposes on the capabilities of the generic method and on how it can be applied. The main research objective of these works is usually the development of the design methodology itself. These shall be called in this thesis "Generic Design Methods" (GDM).

On the other hand, in other works, a very distinct scenario is found. In these cases, the authors start from a particular design case, or set of requirements, and the objective is to design an aircraft according to the criteria of this specific scenario. For instance, the problem formulation is to design a fighter aeroplane for an air-to-ground strike mission with a pre-determined set of enemy defences and assets (82), to design a RPA for a photogrammetric mission in Antarctic terrain (24), or to develop a RPA for a research mission in the Pacific Ring of Fire (25). Usually, in these types of works, the operational scenario and the initial requirements are defined with very high level of detail. Here, instead of tightly following the steps of a previously laid out GDM approaches and applying their general formulation for their particular case study, the authors develop a specific design approach which is usually very interrelated to the kind of problem that is being solved. Therefore, the specific problem is tackled both by developing the design method and within the same work applying it to reach the design of the aircraft that is to comply with the stated mission. In some cases, the authors can use different steps of several GDM as inspiration when creating their specific design approach. The main research objective of these works is the design of an aircraft for an intended purpose, and

the development of the particular design approach is part of the process to comply with the previous main purpose. These approaches will be named “Ad hoc Developed Design Methods” (ADDM).

The main distinction between both types of approaches is that the first one has been developed intended to be applied to a wide variety of design cases and thus has a generic formulation and a broader applicability scope; whereas the second has been devised with a particular design case in mind, thus the design approach is usually presented in a specific manner, and it is tightly interlinked with its specifications. It is relevant to differentiate an ADDM from a case application of a GDM. Whereas in the former a design approach is created as part of the process of designing the aircraft, in the latter the design methodology is the GDM itself and it is usually applied following very tightly its steps. The main differences between both proposed categories are illustrated in a simplified manner in Figure 2-2.

Each of these approaches has its merits. In the case of GDM, they generally have a broader applicability and a higher degree of reusability in diverse design cases. Applicability of a design approach is determined by many factors, including their envisioned scope and the nature of their disciplinary analyses, as commented previously in 2.1.1.. In this case, GDM are developed according to the objective of being generic design methods. The fact that a single method can be used in several applications also permits a more direct comparison between different design cases which have been tackled with the same GDM, as any variation incurred by changing the design methodology is discarded. Of course, these methods also have a designated scope, their applicability is delimited by it (for instance, a GDM intended for the design of transonic transport aircraft will probably not be applicable to short-medium range RPA), but it is still usually wider than that of AADM. In the case of the latter, their reusability within design cases different than the particular scenario for which they have been created could be uncertain, as these methods are very interlinked in their scope to their specific design case. On the other hand, this level of specificity allows them to consider much more detailed aspects of design, allowing for the design method to take into account phenomena and requirements that may not be found in GDM. For instance, knowledge of the orography of the particular region where the mission is to be developed, or the particular meteorological conditions that will be present, which are usually considerations not included in GDM, can be leveraged in these methods to design aircraft which are much more prepared for this scenario, such as in the works of (24; 25; 83; 84).

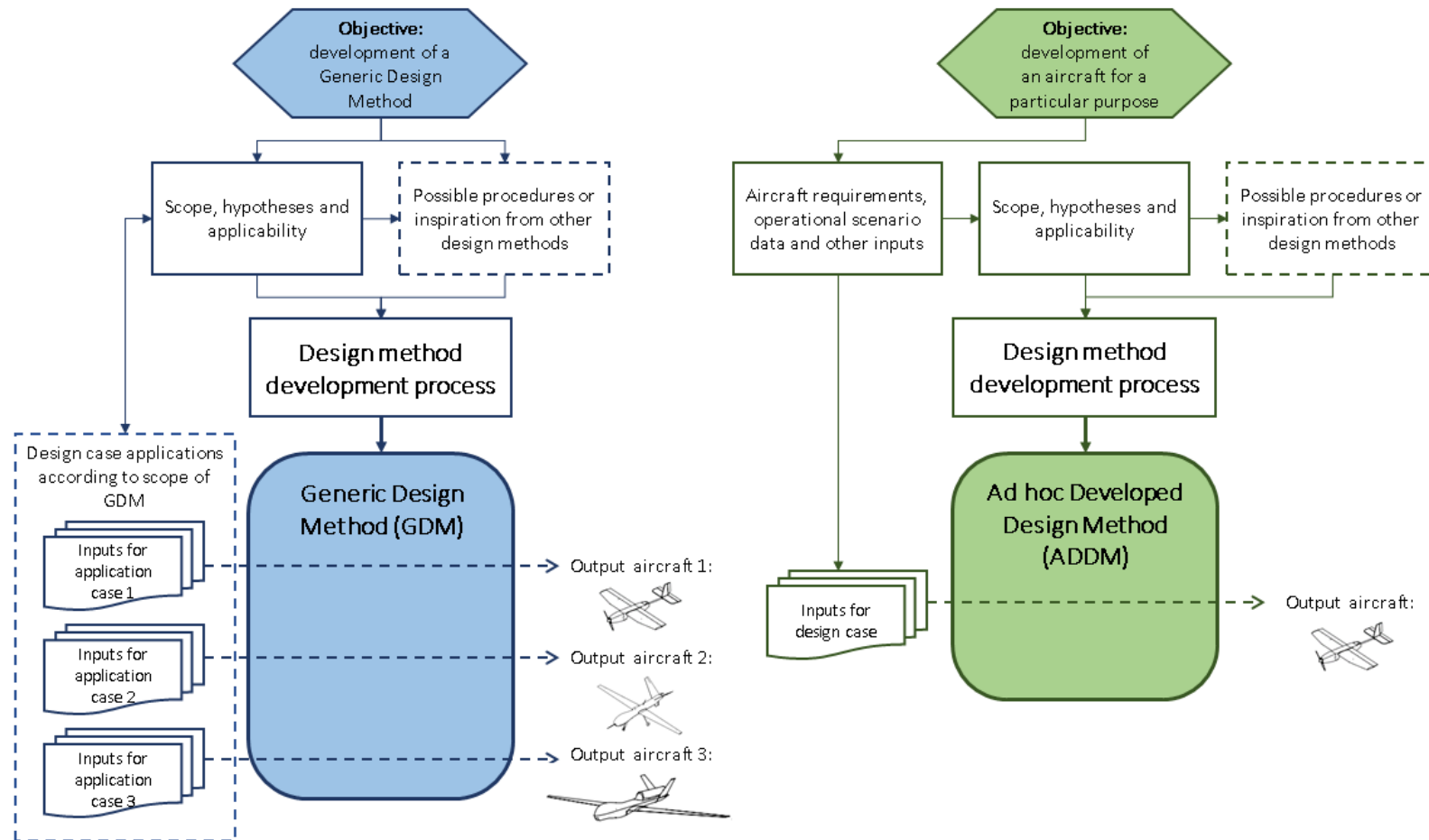


Figure 2-2. Comparison of the rationale, development process and characteristics of Generic Design Methods (GDM) and Ad-Hoc Developed Design Methods (ADDM), following the definitions from the main text.

The distinction between these two lines of work was not found in an explicit manner in previous research, neither specific terms were employed to identify and name these different perspectives. In the case of this thesis, this classification has been made since it is related to both the scope of the design methodologies developed here, and it also serves as a classification criterion for the state-of-the-art analyses conducted in this chapter, allowing to detect which of these approaches is more common within the different lines of work of the state-of-the-art. This allows to extract significant conclusions regarding research gaps and the relationship between the different RPA design approaches. These concepts are also employed through this thesis within more specific state-of-the-art analyses along the different chapters. Furthermore, they are also tightly linked to the type of research contributions to be developed within this thesis, particularly those concerning RCT.3, which shall be of the GDM type. This decision, made in view of the current challenges within the area of RPA design, the objectives of the thesis as laid out in chapter 1, and the findings from the state-of-the-art review, shall be discussed at the close of the present chapter.

2.1.4. Computerised design environments

In the recent years, there has been a noteworthy development of computerised implementations of design approaches, since the possibility of formalising design activities and automating them within a software program presents many advantages. Some of the benefits of setting up software programs implementing aircraft design routines include aiding in the management of the different tasks of the design process, permitting the validation of analysis tools and approaches, allowing to seamlessly perform trade studies among different design alternatives, and expediting the design process through the automatisisation of certain tasks, among many others (51).

The level of sophistication of these design programs has been steadily increasing, tending towards holistic environments which not only conduct design tasks, but also present other qualities such as aiding in establishing design workflows, connecting with external software, and managing large amounts of design data, amongst other aspects. Considering the potential of these design software, in this subsection the concept of computerised design environments is introduced, and their main characteristics are defined. As brought forward within chapter 1, the topic of computerised design environments shall be among those analysed in detail within this part II of the thesis as part of addressing OBJ.2, particularly within chapter 4. Therefore, this subsection also serves as a preamble to the detailed survey which will be conducted therein.

It should be noted that these type of computer programs have received many different names in the scientific literature. They have been called “Automated Design Synthesis (ADS) programs” (51), “design frameworks” (59), “design environments” (17), “aircraft design environments” (59), “computer support tools for aircraft design” (76), “aerospace vehicle design environments” (85), and “air vehicle integrated tool suites” (68), amongst

others. Along this thesis, all the aforementioned terms, along with “computerised design environments” and “design packages” shall be used interchangeably, since there appears to be no consensual distinction between these alternatives.

There is a remarkable diversity of aircraft design environments, with varying levels of complexity and each placing emphasis on different aspects and design challenges (63). Some examples of computerised environments would be, for instance, the Flight Optimization System (FLOPS) (86), the Computerised Environment for Aircraft Synthesis and Integrated Optimisation Methods (CEASIOM) (87), PIANO (88), VAMP-ZERO (89), the Stanford University Aerospace Vehicle Environment (SUAVE) (85), the Fixed-Wing Aircraft Sizing Tool (FAST) (90), the Layered and Extensible Aircraft Performance System (LEAPS) (91), GENUS (59) and AGILE (92), just as a few examples. A wider array of design packages shall be analysed later on within chapter 4 of this thesis, both in the fields of manned and unmanned aeroplanes.

Before moving forward, a definition of what constitutes a computerised design environment shall be proposed for use in this thesis. This will allow to delimit the scope of the analyses conducted in this investigation regarding these computer programs, and also to distinguish them from many other software, such as geometry modellers, tools for disciplinary analysis such as CFD and FEA programs, or flight performance simulators, amongst others. The definition proposed here is heavily grounded on the notion of “design” which was given at the beginning of this section, as it allows to distinguish the concept of design environments from other programs conducting different, albeit related tasks, such as the ones mentioned beforehand.

In this thesis, aircraft design environments have been considered as those software packages which cover the following requirements:

- 1) They encompass at least two disciplines related to aircraft design and analysis, such as aerodynamics, structures, weight estimation, mission analysis, etc.
- 2) The results of the analysis of the aforementioned technical subjects are fed back to the design loop and have a direct influence in either sizing or updating the geometric dimensions of the aircraft which is being created or optimised. That is, the approach is of synthesis, not only of analysis.
- 3) To be considered a part of the design package, modules must be assimilated in the overall design process workflow, meaning that their outputs should have a direct effect on the design or optimisation of the aircraft, thereby resulting in changes to the aircraft concept definition. If the results from an analysis module or tool only serve as a measure of the capabilities of the aircraft concept, and are not fed back to the design process, this component would not be considered to be integrated in the synthesis procedure itself.

- 4) Computerised design environments are not only automated design methods implemented on computer programs, but also tools to aid the designer to conduct the various tasks of the aircraft development process. Thereby, there is usually a significant effort directed towards architecture aspects and software engineering (41; 51; 93). This is a main differentiating point between a design method implemented in a computer code subroutine and a design package itself. Considering the above, certain attention is given to elements such as the program architecture, the organisation of the design problem structure, data models, the interface and interaction with the user, and the information flow from inputs on to the different modules and finally to the outputs of the program and their format. Albeit data models themselves would not constitute design environments, they can be remarkable assets when integrated in these programs.
- 5) The overall design process conducted by the environment falls within the GDM definition given in 2.1.3. Thereby, there is a certain degree of generality on the implemented procedures, and the systematic design process can be applied to a variety of design case inputs, resulting in diverse output aircraft each of which being designed according to their particular requirements.

The definition provided above includes most of the efforts resulting in computerised tools for aircraft design which are available nowadays. However, the technologies and capabilities of computerised environments are also actively evolving in recent times, as it will be seen in detail within chapter 4, so the definition of what constitutes a design package might be subject to change in the future. Furthermore, in the following text, some particular distinctions shall be made between the definition of computerised design environments adopted here and other types of programs such as standalone analysis software or MDO procedures. The objective is to further clarify and delimit the use of the computerised design environment notion employed in this thesis.

There exists a notable variety of software which focuses on some of the different disciplines that intertwine in the design of an aircraft. Such tools cover one or several areas including: CAD, aerodynamic modelling, structural analysis, flight dynamics simulation or autopilot design, amongst others. The objective of these software consists in obtaining adequate and reliable outputs referred to the disciplines of consideration, such as the aerodynamic loads or the structural stresses. Some examples could be the Computer-Aided Three-Dimensional Interactive Application (CATIA) for geometric modelling, Athena Vortex Lattice (AVL) for aerodynamic calculation, and even higher fidelity software such as FLUENT or the NASA Structural Analysis System (NASTRAN) respectively for aerodynamic and structural analysis. These programs are mostly geared towards the analysis of a defined aircraft concept, and unless paired with other tools or included in an optimisation package, the results seldom loop to the geometry sizing of the aircraft, therefore not having a direct effect on its dimensions and design variables (weights, geometry, powerplant characteristics, etc.). Consequently, these tools (which

will be named “analysis software” or “analysis tools” along this thesis, linking with the distinction between analysis and synthesis approaches discussed in 2.1.1), when considered isolate, would fall out of the scope of this investigation. This is also the case for frameworks which link together several programs to perform sequential analyses on an already existing aircraft concept (for instance, an aerodynamic analysis provides the loads which serve as inputs for another program performing stability and control analysis, and so on), and which do not loop back to updating the geometry. However, it is noted that these kind of analysis programs can be integrated as elements within the workflow of design environments (55), as it will be seen in the survey of chapter 4. In this case, they can constitute specific disciplinary modules which operate within an overall development workflow, with their results feeding a loop that modifies the design itself.

On another note, a great effort has been conducted in recent times to apply and develop MDO procedures in the aircraft preliminary design phase. The optimisation procedure of an aircraft considering diverse disciplines can be integrated within an aircraft computerised design environment. In fact, it is noted that some of the most remarkable computerised design environments are built upon an optimisation framework, on top of which they integrate a detailed user interface, data models which allow to connect several modules of the program among them as well as with user inputs and outputs, and other functionalities to manage the overall design process. However, some optimisation frameworks or programs might not cover the above-mentioned fourth point of the proposed design environment definition in this thesis, particularly when they are not integrated within a broader aircraft design suite covering some of the functionalities mentioned here. Thereby, optimisation processes would require these kind of additions so that they could cover all of the points of the notion of design environments expounded above, thus supporting other aircraft development dimensions and aiding the designer in the overall aircraft synthesis process. As an additional clarification regarding MDO, those optimisation frameworks focused on very specific application scenarios (thereby ADDM), or those not covering the analysis of aspects related to the overall aircraft concept (for instance, those which conduct the optimisation of the powerplant, considering the airframe fixed), would also be outside the scope of what is considered an overall aircraft design environment here, due to the fifth point in the proposed definition.

Finally, it should be mentioned that some software frameworks could fall in the boundaries of the design environments definition, particularly considering the recent changes and dynamism in this area, which may challenge traditional concepts. In these cases, a key deciding aspect to identify a software as a design environment would be through the objectives, architecture, and interfaces of the computer program as a whole, which should be concerned with a relatively holistic coverage of design tasks, not focusing only on particular aspects of the design process.

A schematic representation of a notional computerised design environment, according to the definition and particularities highlighted above, is provided in Figure 2-3. As it can be

seen, it would represent a design package for the conceptual design stage, with an initial estimation of the geometry through statistical means, and then a sizing loop where the aircraft geometry is updated, aerodynamic characteristics are computed, and performance is evaluated, until the requirements set at the beginning of the process are fulfilled. Here, an external software, which could be of the likes of X-Foil, Athena Vortex Lattice (AVL) or Tornado, could provide the aerodynamic results, showcasing the connectivity between design packages and analysis software as commented earlier.

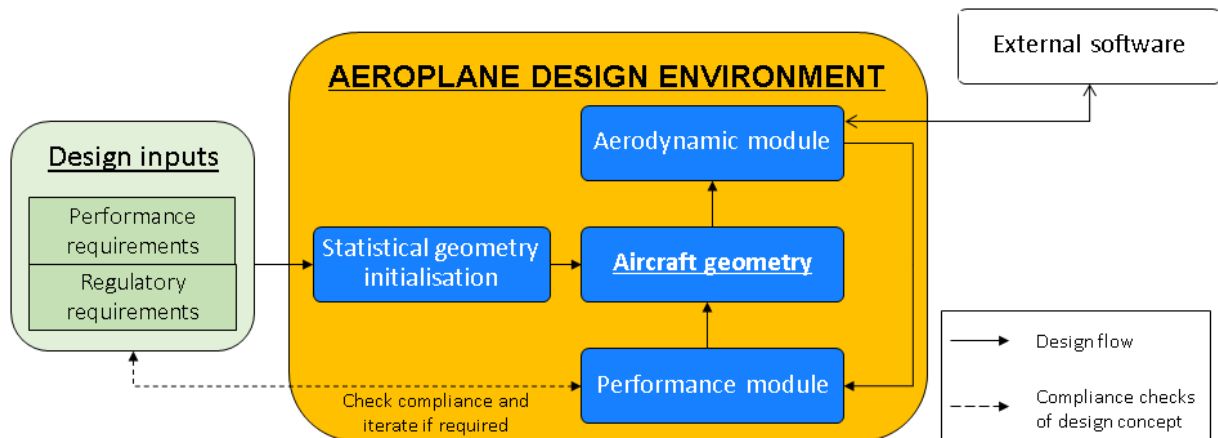


Figure 2-3. Notional concept of a computerised design environment, in this case developed for the conceptual design stage.

As brought forward before, the purpose of these computational design environments is to aid the engineers in the aircraft design process, seeking to improve its efficiency and fidelity (59; 70; 94). For instance, technology trade-offs and sensitivity analyses can be performed by changing the relevant parameters or initial requirements, a process that can be performed more efficiently with computerised environments such as these (51). Design environments are usually modular in nature, which simplifies data exchange (51), and also facilitates their development. Depending on the case, the execution of the modules can be managed by a central control program or management layer, which is usually the norm in environments employed for optimisation, such as in (61; 95). It should be noted that, similarly to the organisation of design approaches in the three phases as discussed within subsection 2.1.2, design environments can also be classified depending on the stages on which they are focused. In fact, previous works in this area also employ the terms of conceptual, preliminary, and detailed design stages when evaluating the potential areas of application of design environments (68; 96; 97), with comprehensive synthesis programs being geared towards a combination of these phases, thus providing analyses at different fidelity levels (51). It has been noted that many design environments are more focused on optimisation than on initial sizing (51; 76). However, conceptual synthesis is also recognised as a fundamental part of the process, as it is key in establishing the baseline design to be optimised in further stages (51). Thus, there are also design packages which place heavy emphasis on the conceptual design step and the

implementation of rapid analysis methodologies, usually implementing approaches based on those of design manuals, such as semi-empirical approaches (51; 59). Some of these environments specifically cover the tasks related to the initial sizing process, which was commented in subsection 2.1.2 to be the first of the steps of conceptual design. Examples of such design packages would be those of (76; 89; 98; 99).

In view of published works analysing the area of computerised design environments (51) (17; 51; 68; 100), two main areas of interest have been identified:

- 1) **Design methodologies and related creative aspects:** this area is focused on the models, hypotheses, and capabilities of the analysis and synthesis approaches which are implemented in the program. The scope and limitations of the tool in terms of the type of aircraft which it can design, the disciplines that it considers, and the level of accuracy of the estimations, among other aspects, are determined by the features of the design approaches themselves. For example, implementing within the performance module an approach which only considers flight profiles and laws corresponding to transport aircraft, would render the design package unable to consider other types of missions. Therefore, the design applicability and capabilities of the design environment are highly dependent on the characteristics of the analysis and synthesis approaches implemented within it. This area is mainly related to aeronautical engineering considerations.
- 2) **Software architecture and computational aspects:** these are features related to the characteristics of the software in terms of structure, workflow, data formats, interoperability, and efficiency, among many others. To allow that the design tasks are programmed and conducted in an orderly manner, it is key to guarantee the seamless connectivity among the different modules, their correct sequencing, and the overall control of the design workflow, among many other aspects (100). Furthermore, in order to adapt the design package to novel concepts and methods, and to make its update easier, flexibility and extensibility considerations are also key. This area is more strongly related to software engineering aspects.

Albeit the main focus of the thesis is in the first of these areas of interest, as the scope is set on the design methods themselves rather than on computational aspects, these two lines of work showcase remarkable connections, as it will be analysed and discussed within chapter 4. Due to the relevance of both areas, the survey conducted therein shall evaluate features related to them both.

In view of the attention that aircraft design environments have received in past years, this area was brought forward in advance within chapter 1 to be among the three for which detailed surveys and assessments will be conducted within the thesis, which is a decision to be further substantiated in view of the survey to be conducted within the following section. Therefore, chapter 4 is dedicated to conducting a review of these design

environments in the broader area of aeroplane design, while also evaluating current developments in the field of RPA design environments. In view of the findings, potential lines of future research in order to accelerate their advancement are proposed. Thus, this topic of computerised design environments shall be greatly expanded upon in chapter 4, where attention shall be given to both the design methodologies implemented within them as well as to the computational aspects.

Furthermore, as it was already anticipated in the introduction, the application of AI in aircraft design and RPAS is expected to have an outstanding impact in the forthcoming years, and there has already been a significant interest from the scientific community in these aspects (64; 65). Specifically, there is also interest in the potential uses of AI in aircraft design environments (76) and design optimisation (101). Aside from possible AI applications in design methodologies and packages themselves, their potential benefit on computational and organisational aspects affecting the design cycle has also been highlighted (102), which also links with the scope of many design environments that aid the designer to cover the design process in a comprehensive manner. Therefore, the topic of aircraft design environments shall also be further explored within chapter 5, where the potential applications of AI-related approaches to enhance their capabilities shall be explored.

2.2. Literature review of current RPA design approaches: main trends and current gaps

The previous section has provided the main background and concepts related to aircraft and RPA design used through the thesis, also introducing the notions of GDM and ADDM approaches that are proposed in this investigation to differentiate two very distinct but complementary approaches to design. This serves as the frame and foundation for the state-of-the-art overview of RPA design methodologies that will be conducted in the present section, and which seeks to address the first of the objectives of the thesis, OBJ.1.

Firstly, subsection 2.2.1 introduces the main reasons for conducting this survey, which link with OBJ.1 formulated in the introduction. The impact that the results from this review will have in the main decisions of the lines of research to follow and the gaps to investigate in the remainder of the thesis will be underscored. Then, subsection 2.2.2 provides a series of points which determine the scope, boundaries and approach for conducting this survey. In subsection 2.2.3, a classification of design approaches according to topical areas is proposed, which has been developed in this thesis as part of the work of the review, and will serve a vital role in categorising the research works to be analysed here. Then, subsection 2.2.4 provides the results of the survey in their own along with their analysis. This then links with section 2.3, where these results shall be discussed, and where they will guide the decisions taken to establish the lines of research of the remainder of the doctoral research.

2.2.1. Purpose and motivation of the review

As it was seen in chapter 1, the design of RPA faces many challenges, and the differences of these aircraft when compared to conventional manned aeroplanes lead to a very distinct paradigm to the traditional one. As mentioned at the beginning of section 2.1, a defining characteristic of aircraft design and analysis methods is their applicability range, and it is recommended that they are not used outside of their scope, as the underlying hypotheses might not hold and inaccurate results could be obtained (6; 11; 50). Classic aeroplane design methods have been developed considering the usual missions, layouts, and overall characteristics of these aircraft. Thus, when studying other aircraft types, such as unconventional configurations or RPA, these methods may not be directly applicable. In spite of this, with the necessary adaptations and through a process of tailoring, these proven approaches could be used as inspiration and baseline for the development of novel methodologies that can be used for other aircraft types, accounting for their particularities and necessary adaptations to the underlying hypotheses and models.

The above-mentioned trend can be observed within the state-of-the-art, where RPA design research has followed a distinct, but parallel path, to that of manned aircraft design, usually revising methods from the latter line of work, which is much more mature, and adapting them to cover the singularities of RPA. For instance, design textbooks considering the particularities of RPA have been published in recent times (6; 10; 13; 67). As another example, albeit there are already various research works dealing with the estimation of rapid-sizing empirical relationships for manned aircraft, such as those of (44; 103; 104); there have also been many publications conducting the same approach but for RPA, such as those of (36; 39; 46), which arrive at remarkably distinct statistical regressions. Adaptations in the methodologies are also required in physics-based approaches. For instance, it has been noted that many RPA present numerous external fixed elements, such as payload bubbles, landing gear, arrester hooks and antennas, which are not the norm in manned aircraft (52). All of these elements usually have characteristics which are closer to those bluff bodies rather than to streamlined ones, albeit there are some exceptions. In any case, the drag provided by these elements, considering their particular configurations and typical geometries in RPA, would also have to be considered in drag estimation methods so as to obtain a representative drag polar. However, in many classical manned aircraft methods, these kinds of external elements are not given as much attention and in some cases, they are not even considered. As it can be seen, it appears that the preferred trend within RPA design research is to examine their differences with respect to traditional aircraft, to then adapt existing methodologies or devise novel ones, contrary to directly employing the large corpus of investigation of manned aircraft directly.

Considering the above, and when addressing the issue of developing new design methodologies for RPA, as is the case of this thesis, it would firstly be necessary to perform a review of the current methodologies and trends which have been developed specifically for RPA in recent times. This will allow to identify the main areas of work, and to pinpoint

potential gaps where novel methodologies can be proposed, which shall be the objective OBJ.3 to be addressed in part III of the thesis. Certainly, as mentioned above, the traditional references of manned aeroplane design also constitute a fundamental source, even if their methods have to be assessed for validity for the case of RPA design and adapted if required. Thus, they shall also be referenced often through the thesis. As that field is much more mature, different design approaches have already been classified and reviewed in previous works, for instance in design manuals such as those of (7; 8; 9; 66), which often present a compilation of diverse analysis or synthesis approaches along with their own proposed models. Usually this organisation of previous models is done by design steps (for instance, fuselage design, initial wing sizing, etc.) or by disciplines and areas of analysis (for example, drag estimation methods, performance methods, etc.), among other possibilities.

In contrast, the distinct and more novel paradigm of RPA design methodologies motivates a particular study, as the design methods here are not as streamlined or organised when compared to those of manned aeroplanes. Up until now, there are few previous references and surveys focused on performing a relatively broad overview of design aspects. Of these, two recent papers stand out. The work of (21) is focused on the main categories of RPA for their classification (fixed-wing, rotary-wing, etc.), the main areas of application of these aircraft, and a high-level evaluation of the foremost design challenges. In this latter area, one of the main lines of improvement in this area as highlighted by the authors would be the development of new design methodologies for RPA, in order to avoid trial-and-error approaches which nowadays seem relatively widespread, and to provide a greater confidence in the efficacy and efficiency of the resulting designs. However, this reference does not compile or examine design methodologies themselves, with the focus being rather on the current types of design of RPA, that is, the architectures and airframe types more commonly found. Then, the work of (33) is also focused on the different categories of RPA. Here, the ones considered are Horizontal Take-Off and Landing (HTOL), Vertical Take-Off and Landing (VTOL), hybrid, and bio-based. The paper compiles the common configurations in each of them, and compares their performance in distinct mission types, highlighting the most promising RPA categories for each kind of operation. Among the conclusions of that work that are related to aspects covered within the scope of this thesis, the versatility of fixed-wing RPA is remarked, highlighting that they can cover many different mission kinds, and that they present noteworthy characteristics in endurance and flight speed interval flexibility. The variety of tail types and layouts is also highlighted, which was already mentioned in section 1.3. However, once more, there is no review or analysis of the design methodologies which can be used to conceptualise RPA with those different layouts.

In view of the above, is considered that performing an overview and classification of current trends in RPA design methodologies as the first main objective of the thesis would constitute a noteworthy contribution, thus leading to the formulation of OBJ.1 as commented in section 1.4. Here, in contrast to previous reviews (21) and (33), the focus

would not be on comparing the current designs of existing RPA, rather on the design methodologies used at the development stage to produce the aforementioned designs. In any case, later on within the thesis in chapter 7, a database of RPA used along the doctoral studies will be presented, and design trends seen in current aircraft will also be extracted and compared to the findings of previous works in this other dimension. Furthermore, as the main purpose of this thesis is to develop original initial sizing methodologies for RPA design, it is required to conduct a literature review on this subject. This will allow to identify the main current trends, and also to detect research gaps, so as to then decide which ones should be addressed by the research presented in this thesis.

Thereby, the main motivations to conduct this type of review at the beginning of this thesis would be the ones listed below, which serve as support for the formulation of OBJ.1 that was brought forward in section 1.4, and which is to be tackled by this review:

- 1) From a descriptive standpoint, to provide an overview of the current landscape of works developing design methodologies for RPA, compiling, and classifying them, so as to capture an updated perspective on this area of research. The purpose is to aid in organising the currently available material in this line of work, as no previous compilations and overview of design methods have been found.
- 2) Using as a basis the previous results, to analyse current trends and gaps within the available trends of design methodologies. For instance, perhaps the area of statistical approaches presents a large volume of previous work, while the one dealing with airworthiness requirement integration in design might have been neglected in previous research and could still have room for improvement. It is sought that this analysis can serve to inform future lines of research in this field, including the selection of the areas where novel design methods will be developed in part III of the thesis. Thereby, this review serves also as fundamental groundwork for the remainder content of this thesis, contextualising it within the current frame of work of the open literature. Furthermore, this survey will be essential for the selection of the disciplines and types of methods that shall be developed, since the most critical state-of-the-art gaps as identified by this review, and which are within the scope of the thesis, shall be prioritised.

As it will be seen, the landscape of RPA design research is varied, with works focusing on many different topics and employing diverse methodologies. Then, the investigations within each topical area also follow their own specific trends and present their particular gaps. Thus, since the objective of this survey is to provide a broad overview of the field, the analysis shall focus, at this point, on the main trends and classifications of design methodologies, rather than on particularities of each individual area. This comparatively coarse approach from a broad perspective shall be complemented later on along the thesis with other more specific literature analyses for each of the topical areas on which the remainder of this research will focus. Thereby, state-of-the-art analyses at different granularity levels shall be found through the thesis, with the current one corresponding

to a broad overview of the field of RPA design, serving as the frame and foundation for the ones to follow.

2.2.2. Review approach, scope and boundaries

In view of the motivations for conducting the review as commented in the previous section, the main approach shall be, from a number of representative and up-to-date works in the RPA design open literature, to extract and analyse the current trends and gaps in the different approaches and topical areas covered by the aforementioned design procedures, all from the viewpoint of the overview of the field. The key is to detect which topical areas have been analysed more extensively, and which are yet to be explored in more detail. This will allow to select the main design approaches in which the focus of the thesis shall be set.

Thus, it is not intended that the survey conducted here gives a detailed insight on aspects such as which equations have been employed for performance modelling, or what combinations of variables have been used in regression studies. Once it is decided, precisely on the basis of the results of the current review, which shall be the main disciplines and areas where new RPA design approaches will be developed within this thesis, the comparatively coarse overview provided here will be complemented with more detailed state-of-the-art analyses. These will then focus on the specific gaps found in each type of design methodology, so as to cover them in the assessments and design methods to be developed further along this thesis. Both approaches are complementary, and each allows to tackle the particular objectives of each part of the investigation presented here.

The design methodologies for RPA shall be referenced through research works in the open literature which investigate new design approaches for these aircraft. Once they have been gathered, they will be analysed and classified according to two dimensions:

- **GDM/AADM:** works will be classified according to their nature attending to the GDM and AADM categories introduced in subsection 2.1.3. This will allow to detect whether the design of RPA is being tackled by the use of generic design methodologies, or rather via ad-hoc approaches being developed and employed to each design case, and if there are particular trends or gaps in works of either kind.
- Additionally, each research publication will be categorised within one of various **topical areas**. This classification follows a similar philosophy to that employed in classic manned aeroplane design manuals to organise their contents and their referred works (7; 8; 9; 66). As mentioned beforehand this classification schema tends to represent various typical approaches towards conducting sizing and optimisation within conceptual and preliminary design, which are usually organised attending to the disciplines of analyses or the design steps covered. In

view of an initial screening of the literature of RPAS, the topical areas that will serve as categories for this dimension will be proposed in the following subsection.

As discussed in subsection 2.1.2, the different stages of the design process are often highly linked to the types of design steps, disciplines and methodologies employed within them. Therefore, each of the topical areas to be proposed for the survey shall also be related to the usual design phases where those kinds of methodologies are employed. To perform this classification, the schema expounded in subsection 2.1.2 will be employed. As mentioned in that subsection, there are different definitions and organisation schemes of the design continuum in the open literature, and it could be the case that the works analysed in the survey each employ distinct criteria. Thereby, to use a homogeneous classification process, the basis to relate each topical area with its corresponding design stage will be those laid out in subsection 2.1.2. Furthermore, it is noted that albeit this thesis is focused on conceptual design, attention will also be given towards topical areas and works focused on the preliminary stage, as both phases interface and are thus interrelated, with some overlap also being feasible for certain design approaches (51).

It is also noted that the same research work, depending on its scope, can be included at the same time in various categories, as long as it simultaneously covers the design activities and characteristics related to each of them.

Having established the main approach followed in the survey, some aspects regarding its scope are given below:

- Since the focus is on RPA design approaches, traditional methods for manned aeroplane design are not covered in the review. As mentioned beforehand, previous references have already compiled and compared some of these works.
- According to the scope of the thesis, the scope will cover works dealing with design approaches for fixed-wing RPA, with a main focus on the conceptual stage. Investigations concerning the preliminary design phase shall also be analysed as commented beforehand.
- The research included in the review has been recovered from the open literature in the area of RPA design. As highlighted by previous research (105), the design approaches which have been followed by RPAS manufacturers to develop their aircraft are mostly proprietary. Thereby, in spite of the high number of RPAS in operation, it cannot be known which design methodologies have been used for these aircraft. Thus, they cannot be readily analysed and compared (105).
- Analysis methodologies which were not integrated within sizing or optimisation approaches would fall outside the scope of this survey, since the focus is on synthesis methods.

- Works will only be included within a certain topical area if they text covers the methods which have been used for it in a sufficient level of detail.
- According to the topic of the PhD thesis, only works dealing with the design of the RPA, namely those focusing on the overall airframe and its geometry, have been included here. There is also a significant amount of research conducted on sizing or resizing of the powerplant, while maintaining the RPA's geometry fixed, such as those of (106; 107; 108; 109; 110). However, these works would be outside the scope of this review. In the same way, those investigations which are specifically focused in systems design, but without also covering the update of the OML itself, would also be considered outside the boundaries of the survey.

2.2.3. Definition of topical areas to group design approaches

Upon conducting an initial screening of the research works of RPA design within the open literature, and as mentioned in the previous subsection, a classification according to topical areas has been developed as part of the work of this thesis. These categories are identified and described below according to the main characteristics shown by the research works covering these types of design approaches:

- **Design manual encompassing approaches:** this represents RPA design textbooks which generally cover various steps and aspects of the design process, thus typically spanning various methodologies. Both qualitative and quantitative aspects regarding configuration selection and sizing are usually included. They seem to follow an approach comparable to the classic design manuals by Torenbeek (7), Roskam (8), Nicolai (11), Gudmundsson (9) and Stinton (48), amongst many others. However, it is noted that RPA design book authors usually tend to focus their texts on the particularities of RPAS (6; 10), and it is expected that the reader uses them as complement to the classic references. It is also highlighted that these works usually also include a heavy focus on analysis approaches, which may then be adapted into synthesis procedures in some instances, as commented in subsection 2.1.1.
- **Statistical estimations:** as commented in subsection **¡Error! No se encuentra el origen de la referencia.**2.1.2, since the level of definition of the aircraft is usually low in the conceptual design stage, typical values and empirical relationships are widely employed at this phase (11; 51). The works classified here are those that have developed a statistical analysis, usually on a database of RPA, seeking to obtain values and trends which can be integrated within initial sizing procedures.
- **Matching diagram constraint analysis:** the works classified here are those which employ any variant of a classical methodology typically used in early manned and unmanned aircraft design which has received many names:

“matching sizing requirements” (8), *“matching diagram”* (111), *“Sizing Matrix Plot”* (112) or *“constraint analysis”* (10) among many others. It is based on obtaining the mathematical equations corresponding to a series of mission and/or regulatory requirements, which are usually then represented on a take-off thrust/weight or power/weight ratio (T_{TO}/W_{TO} or P_{TO}/W_{TO}) versus take-off wing loading (W_{TO}/S_w) diagram, allowing to identify the feasible design space which complies with all of the specifications. It is typically a fundamental step in selecting key variables of the aircraft within the initial stages of conceptual design, particularly parameters related to initial wing and powerplant sizing (8). This approach is distinct from that of a formal analysis involving constraints within an optimisation process, which would be included in the topical area of multidisciplinary optimisation.

- **Integral performance-based sizing:** starting from the initial requirements related to mission range and endurance, these approaches perform a first estimation of relevant design masses such as the Maximum Take-Off Mass (MTOM) or the Operating Empty Mass (OEM), in such a way that the obtained values are compatible with an initial aircraft definition that can comply with its mission specification. This perspective has been widely used in manned aircraft design within the first stages of conceptual design, as seen in (7; 8; 14; 113), and it is usually based on the use of mission profile modelling, integral performance equations, and the use of typical flight parameter values as well as statistical regressions. It should be noted that this approach is much different from those that employ accurate trajectory planning and mission simulation, which are usually leveraged in more advanced design stages, as it will be seen later.
- **Overall initial sizing:** this can be defined as the overall first fundamental step in the conceptual design stage, as commented in subsection 2.1.2, covering from the initial specifications up to a point where both the main design masses, as well as key dimensions of the main elements of the aircraft (wing, fuselage, tail surfaces, etc.) have been estimated. This process can employ, among others, some of the techniques covered in the previous three categories, which are employed in an overall workflow to reach the desired level of definition of the aircraft. This combination of approaches is usually the case of classical procedures of manned aeroplane initial sizing, as seen for example in (7; 9; 11; 48). A key characteristic of an overall initial sizing process as considered in the present investigation is that there is a mathematical dependence of the resulting design on the initial specifications, which seeks both that the concept complies with the requirements, and also that it is not oversized, striking an adequate balance between effectiveness and efficiency, all while employing the rapid methods typical of conceptual design. Thus, an initialisation of a geometry, for instance to guess its initial values in an iterative sizing or optimisation process, would be considered outside of this category, as the geometric dimensions have not been derived

through a rational synthesis process, and at the most have been chosen based on similar aircraft. Works have only been classified here if they cover the initial estimation of key variables from the main components, including the tail surfaces, in a self-contained manner. Therefore, this category would potentially be more holistic than the previous three. For instance, the results from the above-mentioned matching diagram constraint analysis typically allow to estimate the wing's main variables, but it usually does not provide information regarding tail sizing and design masses, so considered on its own, it would not be an initial sizing process. However, when combined with other techniques such as statistical approaches and integral performance based methods, as it is in the case of (8), the conceptual constraint analysis approach can allow to reach an overall initial sizing of the aircraft. Finally, an overall initial sizing approach should include an initial performance estimation of the design concept to ensure at this stage that the corresponding requirements are met. This topical area constitutes a crucial part of the design process, and thus many design manuals ensure that the overall initial sizing is covered, since it allows to have an initial layout and configuration which can then be employed for more detailed analyses.

- **Design-airworthiness integration:** as commented in subsection 2.1.2, airworthiness aspects should ideally be incorporated along the whole design process, following distinct approaches depending on the nature and scope of the design approaches to be populated with airworthiness requirements. The area of design-airworthiness integration can be considered to cover two steps. The first would include the identification and extraction of design criteria from regulations, and the second, the integration of those criteria within sizing or optimisation methodologies. Both steps are strongly connected, as the specific requirements to be extracted from the regulations will depend on the scope of the design methodology itself. This category shall include works covering any or both of the aforementioned steps, as long as they are focused on the connection between design and airworthiness.
- **Structural design:** usually tackled in the late conceptual or early preliminary design stage (10; 11; 12), the selection of layout and sizing of the internal structure is a crucial step towards enabling more detailed analyses at later design phases. Works included here perform the task of sizing the geometric parameters of the structural elements (spars, stringers, ribs, frames, etc.) usually on the basis of the aerodynamic loads, which can in turn be chosen based on airworthiness requirements. It can be seen that this design stage can only be conducted once the aircraft has reached a certain level of definition (for instance, the OML must be defined with a certain level of detail to obtain representative loads) hence its consideration in preliminary design studies.

- **Simulation-based approaches:** these techniques are based on the detailed performance, stability, control and navigation simulation of an aircraft which has already reached a certain definition level. Usually, flight simulators are employed, and the behaviour of the aircraft along the mission profile is carefully examined. This by itself would not constitute a design task, rather an analysis approach. However, the works included here use the results from simulations within a feedback loop to modify the geometry of the aircraft in view of the outputs from the simulation, usually through an optimisation process. Once again, these approaches are typically employed at later stages, as the aircraft aerodynamic characteristics, mass distribution, and stability and control behaviour are often only known with certain level of detail at the preliminary stage. Another reason for this is that these simulation approaches, which strive for a medium-high accuracy and employ more detailed models, have higher computational cost than rapid estimation methods for performance.
- **Multidisciplinary optimisation:** starting from a pre-defined geometrical definition of the aircraft, and considering various analysis disciplines, an optimisation framework is laid out, and upon defining an adequate objective function and constraints, the aforementioned aircraft concept is optimised. The range of variation of design variables is usually not as broad as that of the initial design stages, so the exploration is carried out in a comparatively restricted solution space when compared to that of conceptual design. These approaches are invaluable in the preliminary design stage, as they can leverage medium and even high performance analyses and simulations to conduct a formal resizing process for the aircraft, allowing to reach an aircraft definition with much more accuracy when compared to other approaches.
- **Computerised design environments:** works categorised here are those dealing with the development of design packages, in this case, for RPA. The definition of design environment that was presented in subsection 2.1.4 has been employed as the basis to evaluate which works can be classified here. This topical area has been considered in view of the noteworthy interest it is motivating in recent times both in the fields of manned and unmanned aircraft design.
- **AI-based design approaches:** as it was anticipated in chapter 1, the application of AI techniques within the broad field of RPAS, and also in the realms of aircraft design and optimisation, constitutes an area of current outstanding interest (64; 65). Thereby, works that apply these types of techniques in RPAS conceptual and preliminary design are also compiled here to serve as a basis for the future analyses related to this area that will be conducted further long in the thesis.

As seen from the descriptions above, many of these topical areas are in tight relation. A conceptual representation of their connections is illustrated in Figure 2-4, also showing for each of them whether their usual methodologies tend to fall more in line with the

conceptual or preliminary design stages. Since the relationships of AI-based approaches with the diverse other areas can be more complex, they have not been included in the figure, and their potential connections shall be analysed later on along this thesis. Finally, it is also highlighted that this schema does not intend to be exhaustive, as many more topical areas and connections could be represented. Thereby, its scope is restricted to the classifications employed in this review.

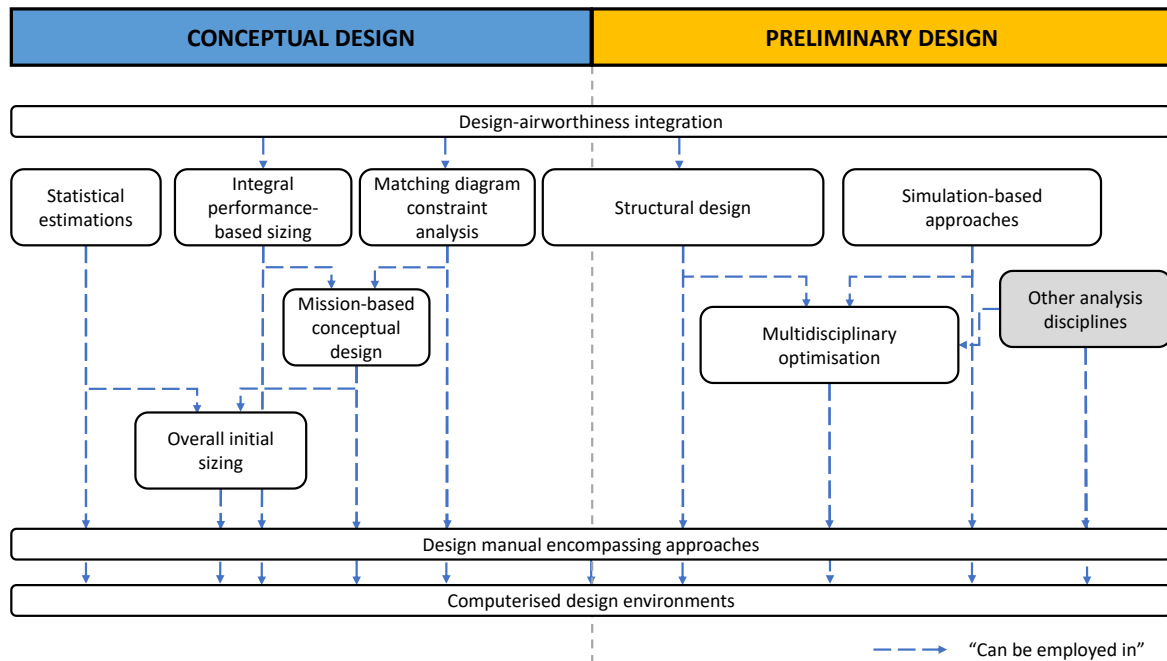


Figure 2-4. Conceptual representations of topics used in the survey, the connections among them, and the typical design phase in which they are employed. Note that horizontal positioning does not represent the order of use in the design continuum.

A significant conclusion which can be extracted from the topical relations illustrated in Figure 2-4 is that there are design approaches that are usually more specific in their scope and which can be used as “building blocks” for other design approaches which are broader in scope. For instance, approaches based on statistics, matching diagram constraint analyses or structural analyses, can all be readily implemented in higher-level design procedures and frameworks such as those of design manuals or computerised design environments, constituting essential design steps within the broader methods. Thereby, albeit specific design approaches only tackle a particular aspect within the overall objectives of the design process, their potential of reusability within other procedures is high.

This relationship between design methods at both a finer and coarser level of granularity shall be key within this review and also in the remainder of the thesis. For instance, gaps found in specific methodologies can also affect the combined approaches, as if a particular approach does not consider a relevant characteristic or hypothesis at the building-block level (for instance, an integral-performance based method that does not account for multi-

role aircraft), then when it is integrated in broader-scope approaches, this characteristics shall not be available either, unless modifications are made at the integration step. Additionally to specific gaps which may be found in particular methods, if there are few approaches available at the building-block level, it could mean that not all the building blocks are available to constitute the higher-level methodologies, so a lack of available or complete methods might also be observed in the latter ones. For example, as integral-performance based sizing constitutes a key part of the overall initial sizing process, if few methods of the first kind are available within the current state-of-the-art, this might explain a coinciding lack of approaches of the overall initial sizing kind, since the latter tend to integrate the former.

2.2.4. Review results and analysis

Having expounded in the previous subsections the setup, approach, and scope of the review, and having laid out the topical areas which shall be used as one of the key dimensions to classify works in the state-of-the-art of RPA design, this subsection now contains the results of the review proper, as well as their analysis. This includes the extraction of key trends in the current works on RPA design, such as those topics which have seen the greater attention; as well as the identification of gaps, representing areas which could present room for improvement regarding the development of additional RPA design approaches.

The representative works on RPA design which have been found in the open literature have been classified in Table 2-2 according to the dimensions and criteria employed within this review.

In the remainder of this subsection, the results from the survey shall be analysed and commented, placing particular emphasis on each of the key areas in which the works have been classified, the attention that each of them has been given within the state-of-the-art, and also the research gaps which have been identified. The following analysis also delves more in-depth into some of the works, so as to detect at a finer level of granularity possible gaps and areas of future work within these topical areas.

Firstly, performing a broad overview from the results gathered in Table 2-2, it can be seen that overall there is a similar level of attention to both stages of design that were evaluated here: conceptual and preliminary design. This supports the idea, as mentioned in subsection 2.1.2, that all design phases, each with its methodologies and perspectives, are fundamental in guaranteeing adequate results from the overall design process. Furthermore, it can be highlighted that, in spite of the remarkable advancements in computational capability and the use of higher fidelity methods, conceptual design remains a very relevant discipline in the field of RPA. As commented in subsection 2.1.2, the main issue in employing of higher fidelity methods in conceptual design is not only one of computational effort, rather one of the level of definition of the aircraft at this point. On the other hand, the aforementioned computational capability increase has been

essential towards recent development on the side of optimisation frameworks. As seen in many recent works such as (19; 114), this has allowed to develop sophisticated design procedures integrating higher fidelity methods and complex simulations within their processes, enabling the preliminary stage to have an enhanced accuracy.

Table 2-2. Compilation of previous research works focused on the investigation of specific design approaches for RPA, classified within the different topical areas considered in the survey.

Topical area	Design phases considered	GDM/ADDM	Example references
Design manual encompassing approaches	Main focus on conceptual design	GDM	(1) (6) (10) (13) (67)
Statistical estimations	Conceptual design	GDM	(15) (35) (36) (38) (39) (40) (45) (46) (47) (115) (116)
		ADDM	(25) (111) (117) (118) (119) (120) (121) (122) (123)
Matching diagram constraint analysis	Conceptual design	GDM	(10) (13) (19) (67)
		ADDM	(25) (111) (117) (118) (119) (124) (125) (126) (127) (128) (129)
Integral performance-based sizing	Conceptual design	GDM	(6) (13) (19)
		ADDM	(25) (117) (118) (121) (122) (124) (130)
Overall initial sizing	Conceptual design	GDM	(6) (19)
		ADDM	(25) (124)
Design-airworthiness integration	Conceptual and preliminary design	GDM	(131) (132)
		ADDM	(24) (118) (133) (134)
Structural design	Mainly preliminary design	GDM	(6) (19) (61) (105)
		ADDM	(24) (118) (133) (134)
Simulation-based approaches	Preliminary design	GDM	(19) (135) (136) (114) (137) (138)
		ADDM	(139) (140)
Multidisciplinary optimisation	Preliminary design	GDM	(19) (35) (61) (105) (135) (136) (114) (141) (142) (143) (144) (145) (146)
		ADDM	(120) (133) (147) (134) (139) (140) (148) (149) (150) (151) (152)
Computerised design environments	Conceptual and preliminary design	GDM	(17) (35) (61) (70) (135) (136) (114) (137) (138)
AI-based approaches	Conceptual and preliminary design	GDM	(19) (35) (45) (47)
		ADDM	(123)

Regarding the distinction between GDM and ADDM works, it is first highlighted that no works within the “design manual encompassing approaches” and “computerised design environments” categories have been included in the latter category, which is in agreement with the definition of the aforementioned topical areas as provided beforehand. Moving on to the overall distribution of works, it is seen that there is a certain evenness between both types of design approaches when considering the overall field, albeit within particular topical areas there are key imbalances which shall be commented later on. It should be highlighted that the areas where there is a comparative lack of GDM approaches with respect to AADM are mainly those related to the conceptual stage, which is the design phase where the work of this thesis is focused.

A remarkable aspect that can be deduced from an overall overview is that, when checking the citations of the diverse references included in each category, and save for two exceptions commented below, it is seen that those of the GDM kind are not repeated as much among different topical areas as much as those in the ADDM category. This is due to the fundamental differences between both kinds of research. Works developing generic methods are usually focused on their topical area exclusively. For instance, the purpose of research such as those of (36; 38; 39) is to develop statistical regressions and models for RPA, whereas those of (131; 132) have a different drive, which is the development of design-airworthiness integration methods. In contrast, ADDM works, owing to their nature, are focused on the design process of an RPA for a particular purpose. Therefore, they cover many of the steps in the design process, as in order to arrive to a sufficiently detailed definition of the aircraft they are developing, they have to encompass various disciplines and procedures along the design continuum in a single work, connecting their results in their overall workflow to make the aircraft concept evolve progressively. Thereby, many different types of methods are developed and applied, and this is the reason for the same reference often appearing in many topical areas at the same time in the case of ADDM.

There are two exceptions to the trend of GDM works mainly appearing in only one area. The first are design manual approaches, which due to their characteristics, tend to encompass various disciplines at the same time, so they appear in that category and also in all of the topical areas which their combined methods cover. Then, there is the case of works in the multidisciplinary optimisation, simulation-based approaches, and in some cases computerised design environments. This is due to many simulation frameworks being leveraged within multidisciplinary optimisation procedures for preliminary design, as commented beforehand and as seen in Figure 2-4. Additionally, these approaches can be integrated in design environments, mostly in those geared towards preliminary design.

Moving on to a more specific analysis of each of the topical areas related to conceptual design, which is the main scope of the thesis, there are several other remarks to be drawn.

Regarding **statistical approaches**, these are relatively widespread, both in matter of GDM and ADDM approaches. At this point, it should be clarified that those within the GDM

side are mainly focused on extracting broadly applicable statistical relationships, such as correlations, obtained from a database analysis including many RPA. In contrast, ADDM approaches included here have mainly dealt with the estimation of values from similar aircraft, or in some cases a few regressions, pertaining to RPA within the same category to that which is being designed. This is done, for instance, in (111) for small RPA with electric powerplants. Thereby, the reusability of statistical results from ADDM would be lower than those of GDM, but in turn they can be more representative of the particular type of RPA which each work is addressing.

In view of the significant number of GDM works within the statistical area, it could be deduced that there are many options in terms of statistical regressions and typical values to aid the designer in the overall initial sizing of the major components of the RPA. However, as it will be seen in detail within chapter 7, where a more thorough state-of-the-art analysis of this area shall be conducted, there are still particular gaps in relation to certain key components sizing. Most of the regressions that are currently available have been estimated attending to general design parameters of the aircraft, such as *MTOM*, *OEM*, wingspan or wing surface. However, there is a fundamental issue on lack of data of RPA when studying certain components such as the tail units, fuselage and tail booms. Therefore, correlations on tail surface areas or data on typical volume coefficients of tails and slenderness of fuselages for RPA are very scarce, which would constitute a relevant hurdle for fuselage and tail sizing in the initial stages of design. From this, it can be seen that there is room for improvement for statistical relationships in RPA, in spite of the moderate number of works which have been found in this area. Due to the facts that statistical estimations tend to be used in many other design approaches, as illustrated in Figure 2-4, this becomes particularly relevant and affects other areas, as it will also be commented shortly below.

The situation with the topic of **matching diagram constraint analysis** is somewhat different. Here, most of the works are within the ADDM area, where there are a few ones pertaining to the GDM category. This can be deduced to be due to the main mathematical expressions being used in the constraint analysis sharing a fundamental physical basis with those used for manned aircraft, such as the ones employed in classic aeroplane design manuals (7; 8; 11; 16). In fact, many of the works within the ADDM category directly reference and employ the equations from those works. The reason is that these mathematical expressions are based on the physics-based modelling of point performances such as take-off, landing, approach or cruise flight, and the physical basis is largely the same for RPA. However, it should be highlighted that there are some variations, such as for hand-launched RPA, and this is the reason for works such as those of (118; 119) developing and analysing particular constraints for those cases. Furthermore, many of the aforementioned aeroplane design equations also employ empirical parameters within the models, which are deduced from statistical trends obtained for those aircraft. Thereby, the direct applicability of manned aeroplane equations could be uncertain if it is not verified whether the empirical constants still hold for RPA. Aside from these hurdle,

there is one noteworthy absence in the case of RPA constraint analysis approaches within the state-of-the-art, which is the integration of airworthiness constraints. This shall be commented later on when addressing the design-airworthiness integration topic.

In the case of **integral performance-based design**, there are fewer works in this area as seen in the table, with a marked lack of those of the GDM type. Many of the research found here, particularly those of the ADDM kind, have directly employed typical initial weight sizing procedures based on mission requirements for manned aircraft, such as those proposed in the works of (7; 8; 51). However, albeit the physical principles of integral performance may be similar in both kinds of aircraft, there could be significant differences in the flight profiles and flight laws of RPA, owing to the wide variety of mission types of RPA, each of which might require significantly different modelling considerations (flight law, possibility of an ingress-egress flight phases, differing values of flight speed, etc.). This could demand more flexible models covering these dimensions where significant variations among distinct missions could be observed. As seen from a more detailed screening of the research included in this category, these aspects and the aforementioned variety in RPA mission parameters have seldom been taken into account. Furthermore, none of these works have considered multi-role capabilities of RPA when performing their design, which as mentioned through chapter 1 is among the most noteworthy characteristics of RPAS. Thereby, there could be room for improvement in this area, as it will be detailed with more depth in chapter 9.

The aforementioned three types of approaches link with the **overall initial sizing area**, as seen in Figure 2-4. Therefore, it can be expected that the current status of this topical area will be influenced by that of the previous three. As seen in Table 2-2, very few research works have been found within the topical area of initial sizing. When analysing in this particular case the influences between topical areas of distinct granularity level as discussed at the end of subsection 2.2.3, to reach an initial sizing definition for a RPA it is usually required to employ a combination of the methods employed in the last three areas, among other possible procedures. Therefore, if few works can be found in the previous three fields, particularly of the GDM type, this can be expected to have an effect in the overall initial sizing processes which are available, as is the case here.

In spite of there being a relatively high number of works in the statistical area, there is a comparative lack of the ones of matching diagram constraint analysis and integral performance, particularly on the side of GDM, as these are the type of methods that can be reused to a greater extent. Thereby, if not all building blocks are available due to a lack of methodologies for some of them, this is a significant hurdle for developing design methods of a broader scope, as it is the case here. There is a further issue, which is that, as mentioned beforehand, the statistical relationships that are currently available do not cover the full range of variables required to propose an initial definition of all main components, with those related to tail surfaces and fuselage being scarce. Therefore, design procedures using the currently available statistical results would not allow to

perform at this stage a sizing of the Horizontal Tail-Plane (HTP), the Vertical Tail-Plane (VTP), or the corresponding tail surface areas for different layouts. Albeit in further stages tail surfaces can be sized through stability and control requirements, at this point the mass distribution of the aircraft is not yet known, as among other aspects, the internal structural layout is yet undefined, so physics-based stability and control considerations cannot be readily applied at this stage (6; 7). In view of the above, if a designer wishes to develop a broadly applicable initial sizing approach of the GDM type, the comparative lack of methods found in generic approaches within the previous three areas constitute a significant hurdle towards assembling a overall initial sizing process that can complete the first stage of conceptual design estimations. Therefore, developing new procedures within the aforementioned three areas could constitute a fundamental asset towards enabling more combined initial sizing approaches for RPA.

Furthermore, and moving on to another way in which specific design approaches affect the broader scope ones as commented at the end of subsection 2.2.3, the currently available overall initial sizing approaches are also influenced by some of the gaps mentioned above for each of the three specific topical areas, such as the lack of multi-role sizing of RPA attending to various simultaneous operations in the conceptual stage, and also a process for sizing tail surfaces through the application of general statistical trends. Overall, combined design approaches which deal with the full initial sizing would also be a noteworthy addition to the methods that are currently available, aiding in achieving a holistic design approach which designers could follow in the first steps of RPA design, in the vein of the philosophy of classic manned aircraft design procedures.

Moving on to **design-airworthiness integration methods**, these have been very scarcely investigated for their application in RPA development. This can be readily explained, as the regulatory framework for RPA is comparatively novel and is still evolving, and developing these methodologies does not only require a detailed knowledge of the regulations, but also their integration within design approaches, a process which may not be straightforward as it will be further developed within this thesis, particularly in chapters 3 and 8. There is another significant gap in this area aside from the low number of works, particularly those of the GDM kind, which is due to the fact that many of the works cited in Table 2-2 have employed regulations that have already been superseded by others. Thereby, albeit these legacy regulations could provide guidance in the design process, the main purpose of these design approaches, which is to arrive at a certifiable aircraft concept, would no longer be achieved. Again, this is due to the rapidly evolving field of RPA which is also leading to an intense rulemaking development and update activity. Furthermore, the gaps found here also flow downstream to other areas attending to their relationships. As mentioned above, the classic matching diagram constraint analysis approach for manned aeroplanes integrates restrictions related to airworthiness requirements, which are essential for delimiting the design space of the aircraft so that it is certifiable. This is not yet the case for RPA, where these type of constraints have not been implemented in the aforementioned technique. Therefore, the

gaps in this area are significant, and have effects beyond their boundaries, so they will be tackled in more depth within the aforementioned chapters.

With respect to **design manuals**, as mentioned above, these tend to include various design steps, offering a more holistic view of the design process, which is also the reason for them appearing in various GDM topical areas simultaneously. Furthermore, they cover both analysis and synthesis methods. There are still few references of this kind in the field of RPA design, with each having a different approach. In some cases, and also depending on each of the areas tackled by these references, the synthesis parts are more qualitative; in others, quantitative approaches for design are given but the equations are not in closed-form, diffculting their reuse in practical cases; whereas in other cases closed-form quantative models are provided, which are the ones most favourable for reuse. Usually, these references are more focused on giving adaptations or particular considerations when compared to traditional aeroplane design approaches, using as a baseline the classic references in the latter field.

Regarding **computerised design environments for RPA**, there are various works which have showed interest in the development of these types of computer programs, which is aligned with the heightened interest in this paradigm seen the field of aircraft design in the last years. The main emphasis of most of these packages is on the optimisation process of RPA, starting from a previously defined configuration with pre-established starting values. This is, for instance, the case of RAMP (61), which is built around an optimisation framework for small RPA (approximately below 50kg). This is aligned with the high volume of references in the topical area of multidisciplinary optimisation, as it will be commented later on. This is also why various references here also appear at the same time within the “multidisciplinary optimisation” topical area, as these works have developed their optimisation frameworks and then integrated them within a design package environment. It could be argued that one of the reasons for the emphasis on optimisation and preliminary design seen in these design packages of RPA is due to the purpose of leveraging medium and high-fidelity physical models, which might more generalisable between manned and unmanned aircraft, thus not requiring as many adaptations as conceptual design approaches.

Various of these design packages also comprise rapid methods which are more aligned with the conceptual design phase, such as UAVOpt (35), which includes a configuration selection approach based on statistical data; or the Collaborative Conceptual Aircraft Design Environment (CCADE) package (70), which applies classic conceptual design methods such as the matching diagram to select the design point of small RPA. However, overall initial sizing approaches that cover in a systematic and rational manner the early estimation of the main geometric characteristics of the aircraft, including a basic definition of the fuselage and tail surfaces, are mostly missing from most of these design environments. This can be expected in view of the gap within the overall initial sizing topical area as seen beforehand. If these kind of methods are scarce in the open literature,

their implementation in computerised environments is also hindered, thus leaving an additional gap in the area of design packages. This again follows the influence that a lack of works in a more specific area has within the broader-scope ones. Works on computerised design environments tend to focus on implementing existing theoretical approaches within these software suites, rather than on developing their own design methods. This dependency between design environments and the methods themselves which are implemented within them further explains some of the specific gaps that can be detected in these environments, as it will be discussed in more detail later on within this thesis.

In various cases, even in those packages developed for the conceptual design phase, the design environment is built around the assumption that the user will already provide an initial geometric estimation of aircraft elements according to previous analyses conducted off-line. However, the rational process as well as the tools and materials which aid the designer to make these decisions are not integrated within the design package workflow itself. Furthermore, the lack of detailed information which is often found regarding the methodologies implemented in these design environments also difficulties their reuse in other RPA design approaches.

Also in relation this topic, it is relevant to note that some design environments mainly developed for manned aircraft have also integrated and demonstrated certain RPA design functionalities. This is for example the case of the design environments GENUS (59; 153), ADEBO (41; 154), SUAVE (93) and AGILE (92; 155). Albeit these are not specifically focused on RPA design, they are mentioned here due to their compatibility with RPA design in certain aspects, and they will be further analysed through the thesis. Most of these are also focused on the optimisation stages, and specific initial sizing procedures for RPA are usually not reported, thus also pointing towards a gap in this area. It should also be highlighted that in some cases various references cited within the corresponding row of Table 2-2 correspond to the same design environment, as is the case of the DECODE package which is covered by references (137) (138). Overall, there are much fewer design packages covering the realm of RPAS than those of manned aircraft, which is a trend coinciding with the observations of previous authors (70), with the latter being a more developed and mature area when compared to the former. The outline provided here of some of the gaps found in RPA design environments will be complemented in this thesis with a more detailed analysis later on in chapter 4.

Albeit the scope of the thesis is focused on conceptual design, some comments regarding **topical areas pertaining mainly to preliminary design** are made in the following. In this phase, the norm is the use of multidisciplinary optimisation to perform the refinement of a pre-defined geometric representation of a RPA, with many works both in the GDM and ADDM sides having tackled this approach. Overall, this topical area is the one where most research can be found in the current state-of-the-art. Simulation-based approaches, which are usually integrated in MDO frameworks, have also been studied

with certain depth, and many of the references appear duplicate from the MDO area, since the simulation programs are typically integrated within the aforementioned optimisation procedures as part of the process of obtaining relevant figures of merit which are then optimised. It should be highlighted that this combination allows them to model complex missions such as stealth surveillance and capture of terrain data (114; 139). Some multi-role considerations have been integrated in optimisation approaches, in contrast to their absence in conceptual methods as commented beforehand (139; 151). However, these simulation approaches usually take significantly longer to calculate, so they would not be feasible for their use in the initial stages. Furthermore, an initial point for starting the optimisation is required, so the area of rapid multi-role initial sizing approaches to provide this geometry initialisation would not yet be covered. If new methods are developed for multi-role initial sizing, they could seamlessly link into the use of the simulation and optimisation frameworks commented above, leveraging the higher fidelity of these latter approaches to perform a refinement attending to more involved details of the missions to which the aircraft has already been sized. On another subject, it can also be noted that there would still be room for improvement in the structural design area. A major hurdle in this regard is that, as seen in (37), RPA present a wide variety of internal structural layouts (monocoque, semi-monocoque, monocoque with foam core, honeycomb, etc.) which can add a layer of complexity to the development of broadly applicable approaches in this topic. Finally, linking this topic with that of airworthiness-design integration, it should be noted that some of the works in this area have integrated certain regulatory requirements regarding load cases, however up until now they are all based on manned aircraft regulations instead of on those for RPA.

Finally, regarding **AI-based approaches**, this is still a nascent area, where few works are found for the time being. However, there is a remarkable interest in further investigation and use of these types of models not only for RPA design, but also in the field of aeroplane design as a whole, as the currently available investigations have shown promising results. Works as cited in Table 2-2 have achieved methods for overall configuration decision-making and initial estimation of certain design variables, which are aligned with the conceptual stage. Advantages have also been demonstrated in the preliminary stage, such as in the enhancement of optimisation approaches and the development of surrogate models from the results of higher fidelity calculation procedures. Overall, there is a rapidly growing interest in this area, and there are still many advantages of the distinct AI techniques to be leveraged, with references such as (64; 65) stating that the use of AI in aircraft design, optimisation and RPA applications can be expected to accelerate in the following years. This highlights the need for research in further connections and opportunities of AI models with design activities, so as to leverage the most adequate AI techniques for each type of application. As a further consideration, and taking into account the relevance of design activities in the resulting airworthiness of the product, it could be advisable to accompany the choice and practical deployment of these models with the consideration of safety and explainability aspects. The topic of AI use in aircraft and RPA design is thus a complex area where these two disciplines intersect, and its background,

previous works, gaps, and possible future directions shall be thoroughly explored in chapter 5 of the thesis.

2.3. Discussion of current gaps and challenges and relationship with thesis research directions

In view of the results from the literature review conducted above, in the present section, a discussion of the main gaps and challenges in the current landscape of RPA design shall be developed. This will lead to an identification of some of the key aspects to be considered towards the improvement of current design methodologies and the development of new ones, with particular emphasis on areas falling within the scope of this thesis. The discussion of these aspects shall be accompanied with some observations from previous works about the main current needs of the RPAS design field.

The final purpose here is to arrive at a decision on the direction of the main areas of research to be tackled within this PhD thesis, considering both its scope and the findings from the survey. This will allow to consolidate and support the decisions made regarding research objectives OBJ.2 and OBJ.3, which were already outlined within section 1.4. Thereby, the information to be presented here complements that which was given in advance in the aforementioned section. Additionally, the outcome of this discussion will also allow to define with a higher level of detail the structure of the thesis already envisioned in section 1.5, as well as the connections between different chapters along the progression of the document.

A summary of the main takeaways found from the previous survey is provided below:

- There is interest both in rapid methods usable within the conceptual design stage, and in more accurate approaches, usually based on optimisation, for the preliminary design phase.
- There is a comparative lack of GDM approaches with respect to those of the AADM kind in some areas related to the conceptual design stage, mainly those of matching diagram constraint analysis and integral performance-based sizing. This does not only result in a relative lack of generic, broadly applicable approaches in these topical areas, but also affects combined approaches such as initial sizing and computerised design environments which integrate the aforementioned more specific methods, as also commented below.
- As discussed at the end of subsection 2.2.3, broader-scope design methods covering more steps of the design continuum (such as overall initial sizing approaches or computerised design environments) tend to integrate as “building blocks” various specific design procedures that have a narrower scope (such as statistical estimations or mission-based conceptual design), which when combined, serve to construct the coarser-level approaches. These connections

and dependencies between topical areas, as illustrated in Figure 2-4, have a decisive influence in the following aspects regarding developments and gaps found in both kinds of approaches:

- If there are few methods available within the design approaches used as building blocks to construct the broader-scope ones, this could affect the possibility of developing methods of the latter kind. This has been deduced to be one of the main reasons behind the lack of overall initial sizing approaches of the GDM type for RPA, particularly due to the lower number of GDM methods available on the matching diagram constraint analysis side and the integral performance-based sizing one.
- Even if there are design approaches available for their combination into broader-scope ones, the possible shortcomings and particular gaps in the ones serving as building blocks also affect the characteristics of the broader-scope design method within which they are integrated. For instance, the lack of multi-role considerations in integral performance-based sizing will also result in this shortcoming being present within initial sizing methods that integrate the former ones. This same reasoning can be applied to other specific gaps found within topical areas, such as the general lack of statistical trends and regressions for sizing the fuselage and tail surfaces, and the lack of airworthiness-based constraints within matching diagram approaches, both of which once again affect the initial sizing approaches.
- On the other hand, it could be said that developments in specific areas also have a positive effect in advancements in related broader-scope approaches. For instance, it can be argued that the widespread investigation in optimisation works has influenced the predominance of preliminary design approaches in design environments. However, if new design methods are developed in the areas covering specific approaches without considering the objectives, aspects, and challenges related to broader-scope ones in which they may be sought to be integrated, the overall reusability usefulness of these specific methods may be negatively affected. For instance, if statistical estimations are developed not accounting for the fact that initial sizing approaches and computerised design environments present gaps in tail sizing estimations, the resulting statistical approach will not cover the needs of the initial sizing one even when integrated within it. This supports the notion that integration and compatibility aspects should also be taken into account when developing specific design approaches, such as for instance, developing all the methods to be combined considering the same aircraft type, so that they do not present issues when combining them into an overall approach.

- There is not only a lack in design-airworthiness integration approaches, but also the currently available approaches are based on superseded regulations. Therefore, due their own value in enhancing the airworthiness of new RPA designs, and also considering the influence of this area in others, a development of updated approaches in this area could constitute a remarkable asset.
- The area of computerised design environments shows a noteworthy interest in later times, but it is affected by a comparative lack of methods and specific gaps in related areas, particularly in regarding initial sizing approaches, which are diffculting future development here.
- The field of AI-related approaches is in its nascent stages, showing remarkable promise and perspectives of rapid growth, but connections with safety aspects and with a wider range of applications of these techniques in sizing activities have yet to be explored in more detail.

In the previous review of (21), which as mentioned beforehand in subsection 2.2.1 is more focused on design aspects rather than on design methodologies, two fundamental aspects to address the main challenges in the field of RPA design were identified: the consideration of the different configurations that RPA can present, and the development of design methodologies themselves. These previous findings connect with some of those of those of the present review.

The first point links with the challenge of layout diversity as laid out in section 1.3 and as also commented in previous research (35). Some previous works have considered qualitative and/or quantitative aspects related to tail layout selection and analysis (6; 10; 35). However, in the area of statistical estimations, there is a general lack of studies on potential variations in design trends associated to the tail layout, which would be extraordinarily useful for initial sizing. In contrast, the study of quantitative differences in design trends due to powerplant choice is comparatively more extended within previous studies in this area (6; 36; 39; 156; 157). This is one of the reasons for highlighting in the review conducted here the specific gap in tail unit statistical estimations, which also affects initial sizing approaches due to the dependency between both areas, and could aid in configuration selection processes within the conceptual stage. Furthermore, this gives emphasis to the relevance of the design methods being flexible, which shall be considered when developing the ones to be proposed within this thesis as part of OBJ.3.

The second point seeks to moderate the use of trial-and-error approaches, which are currently widespread in this field. In this regard, it can be considered that the survey conducted in this chapter, which has compiled and classified several previous investigations on RPA design methodologies, could aid in pointing towards former references which contain approaches that can be leveraged in future RPA design efforts if the designers find them applicable to their particular case, thus potentially aiding in the

reuse of proven design practices. Furthermore, the findings have also pinpointed some potential lines of future work in several topical areas, which can aid to further enhance current design approaches. This potential use of the review findings will be leveraged further along the thesis for the selection of the areas to be studied in more detail and the design methodologies to be developed as part of OBJ.3, as seen in Figure 1-4. Also linking to this point is the comparative lack of GDM methods which has been observed in certain topical areas, particularly affecting the conceptual design stage. These type of design approaches are the ones with broader applicability range, thus being more aligned with the purpose of the second point raised in (21), so these kinds of systematic methods will be the ones preferred when developing the novel design approaches later on in the thesis.

Regarding some of the specific gaps found at a finer granularity level for certain topical areas, it should be highlighted that most of them are related to the particular challenges in the field of RPA design as brought up in section 1.4, many of which still remain unaddressed. Of particular relevance to the areas directly related to conceptual design would be:

- The few studies currently available on statistical trends for tail and fuselage, which links to the layout diversity challenge and to the one related to the lack of applicability of manned aeroplane data
- The lack of multi-role approaches also considering the wide variety of missions of RPA, which is in relation to two associated hurdles as commented in section 1.4.
- The fact that previous matching diagram studies have not accounted for current RPA regulations, linked to the unsettled regulatory requirements challenge.

The identification of these specific gaps here has laid out the ground work for a more in-depth analysis of these areas within particular state-of-the-art analyses to be conducted later on in the thesis for each of the topics on which novel design methods will be proposed as part of the work related to OBJ.3.

With respect to the extended use of optimisation within RPA design approaches, these frameworks have shown remarkable results for the preliminary design stage of RPA, leveraging higher fidelity methods to arrive at an accurate definition of the aircraft. However, as mentioned beforehand, the noteworthy development in this area does not substitute the need for rapid estimation approaches which can perform an initial sizing from a clean sheet. The optimisation studies tend to start from a pre-defined initial layout of an RPA, and usually within the studied works the selection of this initial point is not substantiated through previous methods. Thus, the development of initial sizing approaches that can arrive to this point in a rapid and rational manner could be considered to provide advantages to the optimisation area too, allowing to cooperatively leverage the advantages of each kind of method within their scope, and providing a seamless link between the end of the initial sizing task and the start of the optimisation

process. It is also noted that in most cases the optimisation framework only conducts small changes in the design variables, with variations of a few units or ten percents over the baseline, as these procedures tend to operate within a more focused design space when compared to the expansive one explored in conceptual design. If larger intervals of design variable changes are considered, the optimisation can usually take various hours or days to finalise, unless it is complemented by the use of surrogate models or AI-based approaches.

Thereby, with the combination of initial sizing procedures and optimisation, the latter strategy can potentially be leveraged in a more efficient manner within design spaces which are delimited to a higher degree, as they could start from an already proven initial design point which represents a feasible design concept according to the requirements. This combined approach and its advantages has already been demonstrated in the recent work of (19), which employs a complete approach including an initial sizing procedure followed by an optimisation of the baseline configuration, leveraging the strengths of both kinds of methods. This supports the emphasis on the development of new conceptual design methods within the frame of this thesis, so as to complement the very high number of optimisation frameworks that are currently available as seen in Table 2-2.

As already commented beforehand in this text, various authors do not recommend the direct application of manned aeroplane design methods within the realm of RPA design. In spite of this, it has been observed that some previous works included in this survey have employed such procedures, sometimes without prior adaptations. This has been observed to a greater extent in topical areas where fewer particular methods for RPA sizing were available. Albeit this is a rapid option to cover some of the aforementioned gaps in certain topical areas, the drawbacks of this approach have already been discussed previously in this text. This further emphasises the need for developing new methods for RPA so as to ensure that accurate and representative results are obtained in future design efforts. The direct reuse of aircraft design methods could even be argued to be one of the reasons for certain specific gaps commented beforehand still being present, such as the lack of integral performance-based multi-role sizing models. Such gaps tend to be related, as discussed above, to particular challenges of RPA. Thereby, if methods from manned aeroplane design are directly reused, and no adaptations are made to account to the particular issues of RPA design, these particular gaps will still remain. Furthermore, this would not allow to leverage the potential of considering certain particularities of RPA which are precisely among their main strengths. Thereby, both in terms of truthfulness of the design solution reached, and in order to leverage many capabilities of RPA which may have a great impact on their design, it is proposed here that research on novel initial sizing methodologies for these aircraft constitutes a noteworthy prospect.

Overall, the couplings among the different gaps, and how the ones in some topical areas affect others, constitutes one of the most relevant aspects covered by this literature review. In particular, the lack of available methods, gaps, and shortcomings of more

specific design approaches can affect the feasibility and characteristics of broader-scope ones which integrate the former ones. As an example seen beforehand, an integral performance-based method which does not cover multi-role sizing of RPA, when used within an overall initial sizing process, can be expected to make the broader process also incompatible with sizing multi-role aircraft. Considering the above, within the context of this thesis, it is considered key to investigate and address certain gaps at the level of the specific approaches, so that after addressing them, these improvements can also be leveraged within broader-scope ones which present related gaps. This is one of the key reasons for tackling, within the context of OBJ.3 of the thesis, the development of novel design methodologies covering different specific topics, addressing for each of them some of the foremost gaps detected beforehand.

The choice of the specific disciplines themselves to be covered as part of OBJ.3 will be made not only attending to the aforementioned particular gaps within each topical area and their potential influence in broader-scope topics, but also taking into account areas have received comparatively less attention in previous works, specifically regarding design approaches of the GDM kind. In particular, it has been found that there are currently few works and also remarkable specific gaps within the topical areas of integral performance-based sizing, design-airworthiness integration, and overall initial sizing. Furthermore, albeit other areas have been subject to a greater volume of previous research, some specific gaps found within them also pinpoint them as potential ones where novel methodologies could be developed. These include the areas of statistical estimations and matching diagram constraint analysis. Considering the relationship among these topical areas which could be candidates for the development of novel design methods, with the initial sizing one covering a broader scope than the others, a substantial prospect for the contributions of the thesis could be the development of an overall initial sizing methodology which combines various novel approaches developed within the other areas which can be integrated in the former.

Albeit the findings of the survey conducted here already capture a preliminary image of the specific lines of research to be tackled within OBJ.3, the final selection of the topical areas where novel design methodologies will be proposed shall be left for the start of part III. This is according to the connections among the objectives of the thesis as illustrated in Figure 1-4, where it was brought forward in advance that the findings obtained from addressing OBJ.2 (which seeks to perform an assessment of various key topics within the broad area RPAS that present connections with the field of RPA design) will also influence the decisions made to direct the efforts of the final part of the thesis. Precisely another one of the reasons for conducting this survey is also to detect these key broader topics which will be studied in the remainder of this part of the thesis, as also showcased in Figure 1-4.

Attending to the definition of OBJ.2, the topics to be studied as part of its would not only be related to the field of design, thus being covered among the areas that have been

included in this survey, but they would also represent fields of current outstanding interest in the overall landscape of RPAS. The specific topics to be investigated in this line of research have already been brought forward in advance within the introduction, but they will be substantiated below, now also supported by the findings of this survey.

As it will be commented below, these topics do not only share connections among themselves, but links can also be found with other more specific design topical areas, some of which may potentially be among the ones for which novel design methods will be developed as part of OBJ.3 of the thesis. Thereby, aside from the standalone interest in studying the key topics of OBJ.2 to be laid out below, it is also essential to thoroughly assess them so that the findings from this study can also aid in the decision of the particular disciplines of OBJ.3 and set additional criteria to those discussed above towards the development of the novel design methods to be developed in part III. This way, upon beginning part III, the aspects discussed in the current chapter shall be combined with the conclusions derived from the evaluations of OBJ.2, and with both information sources, the main guiding criteria for OBJ.3 shall be finalised.

From the above, it is key at this point to substantiate the topics which will be at the forefront of the reviews and assessments to be conducted as part of OBJ.2. As already brought forward in the introduction, these areas shall be selected attending to their connection with the overall field of RPA design as well as with other particular areas within this broader subject, as already mentioned along the previous lines. Furthermore, it is also highlighted that the areas which will be selected also have a noteworthy significance by themselves, as they are among the topics with a higher dynamism and interest in the overall field of RPAS, as it will be mentioned below.

Firstly, as seen from the findings of the survey and as mentioned above, the topic of design-airworthiness integration is among the ones showing the most remarkable gaps and need of an update in the current RPA design landscape. As commented when defining this topical area, the approaches considered here include both the extraction of airworthiness requirements from the applicable regulations, as well as their integration in design methodologies. It would not be possible to develop design approaches covering these two aspects if the applicable standards and rules are not scrutinised beforehand. As mentioned in chapter 1, the field of RPAS regulations is currently evolving at a rapid pace, and the standards in place nowadays differ significantly from those of a few years back. Thereby, even though there are previous works reviewing the regulations of RPAS, most of their findings might not be fully usable nowadays. This highlights the need to perform an analysis of the defining aspects and nuances of the RPA regulatory paradigm, as well as an up-to-date review of current regulations, before tackling the development of design-airworthiness methodologies. Aside from gathering and analysing the current standards, their characteristics from the viewpoint of their integration in design approaches should also be assessed, since this can be expected to have an outstanding effect in the challenges which must be overcome by the design-airworthiness procedures to be developed.

Finally, as also introduced in section 1.1, the area of airworthiness regulations of RPAS is among the most dynamic ones in the broader scope of the realm of these aircraft, which constitutes another motivation to provide an up-to-date overview of this outstanding subject as related to the main topics of the thesis. With this, the need for OBJ.2.1 within the frame of the thesis, as well as its placement before OBJ.3, can be substantiated.

Moving on to the second key area, which will be that of computerised design environments, it can be seen that this topic shows remarkable promises, as also seen beforehand in subsection 2.1.4 about the ways in which they can contribute to the designer's work. In the field of RPA, with the many challenges it is facing, these kind of tools could provide an invaluable asset to tackle some of the main hurdles associated to the design of these aircraft. However, this field is still under development, particularly in comparison with the much more mature area of manned aircraft environments. Therefore, to complete the overview provided here, it is sought to conduct a much more in-depth review on the topic of computerised environments for RPA themselves.

Picking up again the thread of the connexion among the diverse topical areas, and since it can be expected that the novel design methodologies to be developed within this thesis as part of OBJ.3 can also be integrated within broader-scope approaches such as computerised design environments, their potential reuse within them should also be considered when developing the design methods at the more specific level. Furthermore, the current particular gaps and needs of RPA computerised design environments should also be taken into account, so that the efforts when developing the specific design approaches as part of OBJ.3 can be leveraged both at their particular level, as well as envisioning their future integration in design packages. The perspective of making the novel design methods aligned with their use in design environments is not only expected to influence the content and models of the design procedures themselves, but also the guiding philosophies when developing them. For instance, it will be seen that computerised environments tend to follow a modular approach with interoperability among different design disciplines or steps. Thereby, the new design methods to be developed in part III of the thesis as part of the tasks related to OBJ.3 could be built in a modular manner, so as to enhance their reuse in future design environments.

The above-mentioned perspectives set up the need to conduct a thorough review and assessment of the current landscape of aeroplane and RPA design environments, evaluating their current status and future needs towards their use for RPA design, both in terms of overall capabilities and of specific methodologies. This should be done before addressing the development of the novel design methods to be proposed within this thesis, so that any findings can be considered at this point to make the design approaches aligned with the needs of design packages too. This substantiates the relevance of OBJ.2.2 within the frame of the thesis, and underscores that it should be carried out within this part of the thesis before starting the tasks related to OBJ.3.

Finally, as mentioned beforehand, the topic of AI-related design approaches in RPA is still starting to be explored, but shows remarkable promise, which is also seen in previous works within the area of manned aeroplane design such as those of (76; 101; 158). However, before specific design methods based on AI models are developed, it would firstly be required to more thoroughly explore this paradigm, analysing its opportunities and main challenges. It is noted that the topic of AI in itself is receiving much attention in the broader field of aviation. The International Aviation Authorities see both great potential for AI in ways which could even improve aviation safety, but they also highlight the risk that would suppose if AI approaches were applied without adequate safety management. Going back to its potential connections with design tasks, firstly some background should be provided on the distinct types of AI approaches, which along with previous works can enable to reach conclusions regarding the ways in which dissimilar AI models could be aligned with different design approaches. Furthermore, and as it is being currently demanded within the field of aviation, safety assurance aspects should be taken into account when developing and deploying AI-based applications. Due to the impact of the aircraft development activities in the safety of the final product, this should also be the case of AI models employed for aircraft design. Furthermore, this links with the topic of airworthiness which is also among the main fields of research of the thesis. As the field of AI itself is very broad, complex and dynamic, and both the connections of these techniques with design and safety aspects are sought to be explored, all of this leads to the need of conducting a particular study, which will be covered by OBJ.2.3 of the thesis. With the purpose of investigating a particular are of AI-related approaches within aircraft and RPA design, this shall also include the assessment of the opportunities and challenges of using ontologies as a knowledge representation paradigm to enhance aspects related to computerised design environments.

With the above, one of the main purposes of the review conducted in this chapter, which is serving to inform and decide the research directions and priorities of the thesis, has been accomplished. Aside from fully defining the specific purposes within OBJ.2, which will be tackled in the subsequent chapters, its findings have also provided key guidelines for OBJ.3. However, the specific lines of work, design disciplines, and criteria when developing the novel design methods to be covered through this latter objective shall be fully substantiated within chapter 6 once the assessments of part II of the thesis are finalised, as brought forward previously in Figure 1-4, and as commented above. Figure 2-5, which is complementary to both Figure 1-4 and Figure 1-5, summarises the main connections of the survey findings with the following chapters and research decisions of the thesis.

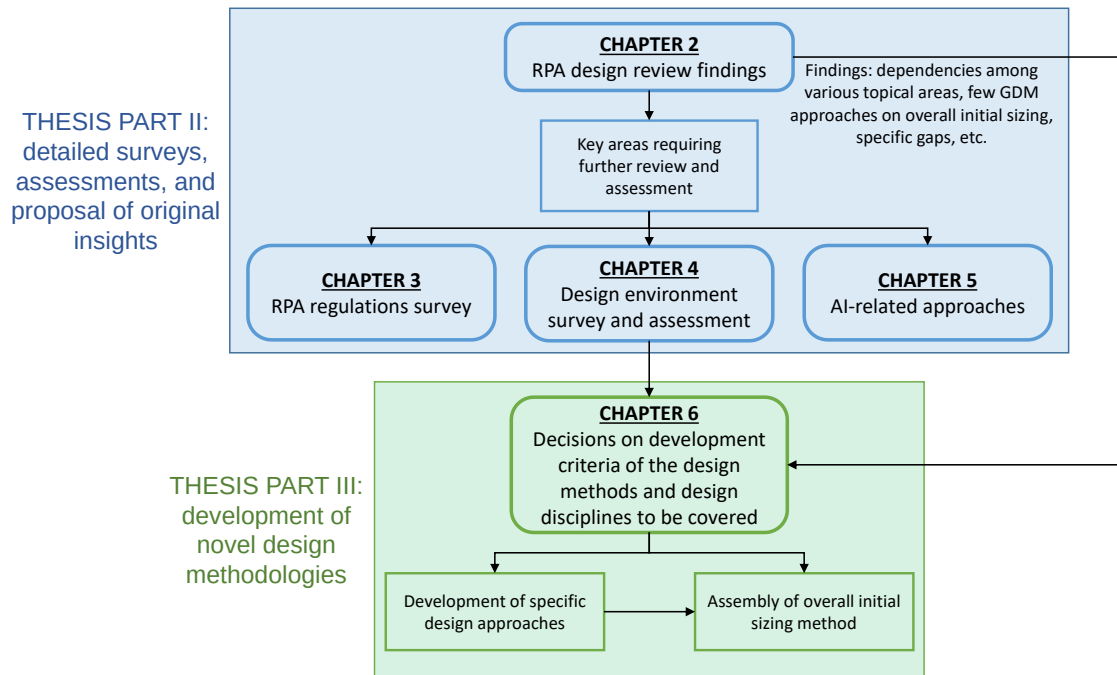


Figure 2-5. Summary of connections of findings of the overall RPA design survey with other chapters and parts of the thesis.

The continuum between specific design methodologies at a finer level of granularity and broader-scope topics and approaches at a coarser level has thoroughly been discussed within this section and the previous one, along with the dependencies among these distinct kinds of procedures and how the developments and gaps in those of one kind influence the other. It has been seen that it can be advantageous to develop the specific design approaches accounting not only for their particular gaps, but also attending to the needs and gaps of the ones at a coarser level, so that the integration of the finer approaches into coarser ones can be favoured. This implies a certain flow of findings from the general levels to the more specific ones, which is according to the fact that OBJ.2 (covered in part II) deals with broader topics, and the conclusions extracted here will influence the decisions regarding OBJ.3 (covered in part III) in relation to the initial sizing method to be developed there, as well as the specific conceptual design approaches which will be used to build the aforementioned initial sizing process. At the same time, and now focusing only on the methods to be developed as part of OBJ.3, these also include two distinct levels of granularity: the overall initial sizing process, and the conceptual design approaches which will be used to build it, so a further information and needs flow from the first one which is more general, to the second group which represents approaches at a finer level, can also be seen.

Once the specific design approaches have been developed, they should then be integrated to build the envisioned initial sizing approach. This follows a different trend, which is bottom-up, going from the finer level to the coarser one. Once the initial sizing method combining the approaches to be developed as part of OBJ.3 has been established and

tested, the foremost goal of the thesis will have been achieved. However, it would also be informative at this point to discuss how the resulting design methodologies could be further leveraged regarding the higher-level paradigms from which needs were extracted beforehand, namely those topics covered in part II, thus going back to a higher degree of generality. This can then be rounded off by providing a set of concluding remarks of the potential impact of the developed methodologies at the level of the RPA design paradigm, which is the highest level of generality, and also the one which has been followed in this chapter with the overview of the general RPA design paradigm.

In view of this, it can be considered that there is a top-down process of criteria extraction and implementation in finer level design methods, followed by a bottom-up workflow where, in the first place, the assembly of the overall initial sizing method is conducted to complete the goals of the thesis, and then, the discussion and conclusions which follow can evaluate the obtained results from the viewpoint of higher levels of generality. This has been illustrated in Figure 2-6, where two dimensions can be seen: the continuum of the development of the thesis research, and the level of generality of the topics covered at each step. Furthermore, the connections between the different steps and the parts of the thesis where they are covered is shown. This sequential top-down and bottom-up flow underpins the organisation of the remainder of the chapters of the thesis, and is aligned with the order in which the research objectives shall be covered.

With all the above, the main directions for the research to be conducted in the PhD thesis in the following chapters have been decided, and a more detailed workflow has been achieved which organises the topics and chapters through different layers of granularity. Thus, it is be considered that the purposes of OBJ.1 have been covered.

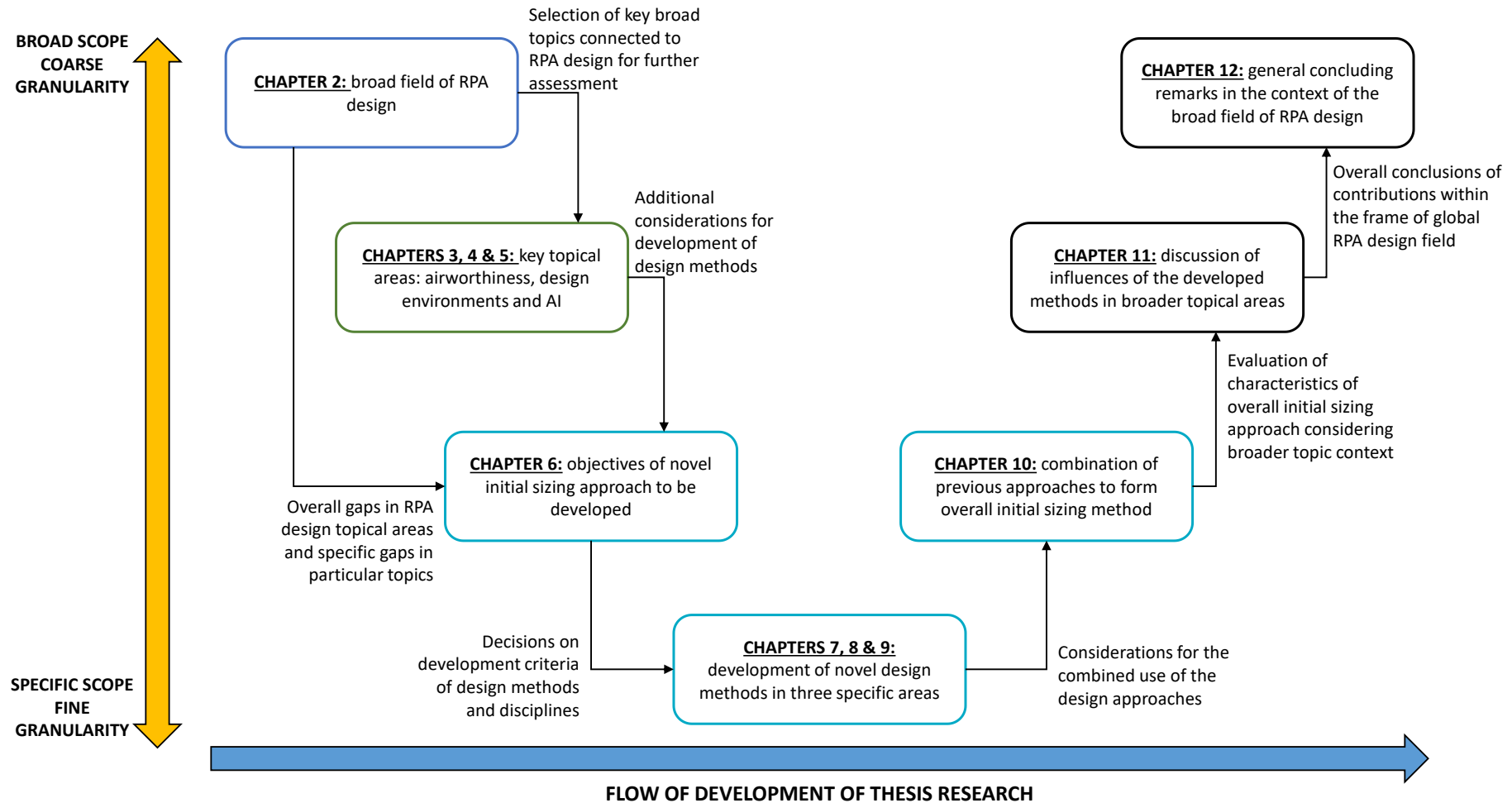


Figure 2-6. Organisation of the contents and chapters of the thesis attending to both the research flow and the level of granularity of the topics at each step. The connections and influences of the broader topics on the more specific ones, and vice-versa, are also shown.

2.4. Summary and conclusions

In this chapter, the essential concepts related to aircraft and RPA design which serve as the theoretical foundation to the development of the research of this thesis have been introduced. This includes the GDM and AADM notions, which have been proposed within the context of this investigation to classify two very distinct kinds of design approaches. Both the theoretical background and the aforementioned concepts shall be used through the remainder of the research as a basis for many future analyses and decisions.

The foremost purpose of this chapter is to carry out the broad literature overview of RPA design, according to needs of OBJ.1. The main approach of this review has been to analyse, at a coarse level of granularity, a representative number of works which propose and apply design methodologies for RPA. These have been classified according to a series of topical areas that have been proposed as part of the survey itself, and which represent key disciplines and design steps both in the conceptual and preliminary stages. Furthermore, the works have also been classified by the design methodology type (GDM/AADM). By itself, this survey provides an up-to-date overview of the design methods which are available within the open literature, identifying the current trends and gaps. The analysed information includes an evaluation of the volume of previous research in each of the topical areas as well as an overview of the specific gaps which are found in each of them. Furthermore, taking into account the relationships and dependencies between the different areas as illustrated in Figure 2-4, the ways in which shortcomings and gaps within some of them influence others have also been discussed, showing an agreement between the identified relationships of the topical areas and the findings in view of the works of the open literature regarding the lack of methods and gaps in those which are related. The following points summarise the foremost conclusions that can be extracted from the review itself:

- 1) The tight links between specific design approaches and broader-scope ones (with the second ones being usually formed by a certain combination of methods of the first kind) should be taken into account when investigating both kinds of approaches. In particular, before tackling the development of novel design methods at the fine granularity level, it is also key to consider the characteristics and needs of the broader-scope ones to enhance the reuse, usefulness, and integration of the finer granularity methods in the coarser level ones.
- 2) In view of the above-mentioned relationship among different topical areas and their effects, it can be considered that some gaps, particularly those found in the specific methods, have a more extended impact in the broad RPA design realm, since they affect both their design approach as well as other ones in which these are integrated.

- 3) GDM methods tend to have a higher applicability range, so their scarcity in some of the topical areas does not only affect the available options for RPA designers, which might lead to resort to manned aeroplane approaches or to trial-and-error methods, but this lack of available methods also has an impact on broader-scope approaches which require to cover these topical areas. Therefore, the development of new GDM approaches in the areas where they are more lacking would be advantageous.
- 4) There are still many RPA design challenges, such as those expounded in section 1.3, which are not yet fully covered by currently available design methods. Some of these include the development of multi-role RPA sizing approaches, the consideration of different tail configurations earlier in the design process including an initial sizing of these surfaces, and the introduction of airworthiness requirements.

All of the aforementioned findings and conclusions do not only have value by themselves as part of an updated survey on the field, but foremost, they serve as a foundation to decide the further research directions of the thesis, avoiding repetition with respect to previous works and already available methods, and directing the investigation efforts towards relevant gaps. In this way, the findings serve to substantiate and elaborate the remaining two research objectives of the thesis OBJ.2 and OBJ.3. Albeit each of the topical areas presents different areas of possible improvements, the main focus has been on those approaches aligned with the conceptual design stage according to the scope of the thesis. In this way, the influences of the review findings in the aforementioned objectives, which were discussed in detail in section 2.3, are summarised below:

- With respect to **OBJ.2**, it is decided to tackle this one first following the first of the conclusions from the survey listed above, since this objective deals with broader topics which have relevance in the overall field of RPAS and also present promising connections with the design process, some of which are yet to be explored in further detail. Thereby aside from the value of these studies by themselves, their findings will further influence the novel design methodologies to be developed as part of OBJ.3. Going back to OBJ.2, the selected topics have been those of RPAS regulations, computerised design environments, and AI-based design approaches. These do not only represent topics with relevant connections and possibilities in relation to RPA design. From a broader perspective, they are currently among the most outstanding areas in the overall realm of RPAS, which further supports dedicating a special effort to studying each of them and seeking to leverage to a greater extent their possible synergies with RPA design activities.
- In relation to **OBJ.3**, the final decision on the approaches to be covered by it, as well as the criteria to be used in the development of the design methodologies, shall be expounded in chapter 6, once the conclusions from the studies related to OBJ.2 are already in place and can also be used to inform the developments of part

III. For now, some guidelines can already be extracted from the findings of the review conducted here. The efforts of OBJ.3 shall be focused on methodologies of the GDM type, as these have larger applicability ranges and can thus be more readily reused in RPA design efforts and also in broader-scope design approaches. Regarding topical areas, the emphasis shall be on those where a low volume of works can be found nowadays, as this results in less options for the RPA designer when selecting the method to follow, and also on those where specific gaps have been found, particularly those related to the main challenges of RPA design as laid out in section 1.3. Specific design methods at a finer granularity level shall also be prioritised, due to their higher reusability potential, and also to mitigate some of the gap couplings seen in broader-scope methods which are connected to a lack of methods in the finer level of granularity ones. This can aid to cover some of the root causes for similar gaps found in this review through approaches of diverse granularity levels, allowing to leverage the fact that solving a gap in the finer level methods can as a consequence solve the same issue in the broader-scope ones. With all this, the topical areas which stand out the most towards directing the efforts of the thesis are the ones of statistical estimations, matching diagram constraint analysis, integral performance-based sizing, design-airworthiness integration, and overall initial sizing. It is envisioned that the latter topical area can be covered by the combination of the methods to be developed according the previous ones. This will also allow to explore the specific hurdles of the area of initial sizing which usually has a slightly broader scope.

Therefore, it can be seen that this review has been a fundamental asset to decide the following steps and lines of research of the thesis. Regarding the remainder of part II, the specific topics selected in relation to OBJ.2 shall be studied in detail within each one of the remaining chapters of this part, including an assessment of their connections and possible influences on design methods at a finer level of granularity to further inform the decisions regarding OBJ.3, so that the design methods developed as part of this goal not only cover the gaps and needs within their own areas, but also serve as building blocks towards their future use in broader-scope ones. The findings from this chapter shall also influence as mentioned above the decisions made at the start of part III regarding the novel design methods to be developed, which shall also be informed by the findings of the remainder of part II, as showcased in Figure 2-6. Thus, the survey conducted in this chapter serves as a foundation for the further reviews, analyses and contributions to be carried out within the thesis at different levels of granularity, and therefore its impact on the overall research is significant, which is among the reasons for the effort carried out here. Further chapters shall provide reviews and analyses of their specific areas at a finer level of detail, which shall complement the broader one found here.

Overall, it can be seen that the field of RPA design constitutes a very broad and varied realm, where efforts of many different kinds are being studied. This reflects the complexity of the tasks of aircraft design, as well as its multidisciplinary and

interconnected nature. Bearing in mind the tight links between the different topical areas, it can be considered that taking into account a broad view of the field could aid future efforts in the development of novel design methods, which may then consider not only the current status of their specific fields, but also the way in which they connect to others, so as to maximise the reusability of their approaches and their seamless connections with other methods from related topical areas. This viewpoint shall be considered in the remainder of the efforts of the thesis within the scope of the design methodologies developed here. Finally, it can be expected that, considering the growing interest in the field of RPAS, the landscape captured by this survey will evolve in the near future, offering a higher diversity of RPA design methodologies with distinct scopes and hypotheses, thereby providing the designer with a higher variety of tools to carry out more effective and efficient designs of these aircraft.

3. RPAS REGULATIONS SURVEY

In view of the findings of the review conducted in chapter 2 about the overall RPAS design domain, there is a need for new design methods for RPA that consider airworthiness requirements. The first step towards creating those methodologies is to investigate the applicable regulations for RPAS, so as to identify the sources from which airworthiness design criteria and constraints must be extracted. This is aligned with OBJ.2.1 of the thesis, which has been formulated not only so that its outputs can provide the fundamental groundwork required for the subsequent development of airworthiness-design approaches, but also taking into account the overall interest and dynamism that the area of RPAS airworthiness and rulemaking is showing in recent times.

Considering this, the current chapter conducts an up-to-date survey of the main regulations involving design and operational aspects of RPAS. Albeit aviation regulations cover many different topical areas, these two have been selected due to their connection with the core topics of the thesis. Initial airworthiness requirements are strongly related to aircraft design and production (159), and they are among the regulatory aspects which have historically been considered most extensively on aircraft design methodologies due to the restrictions that they establish on the design space (7; 8; 48). Operational aspects are mainly related to the aircraft missions, which is also one of the main topics of the thesis. Furthermore, it will be seen that in the realm of RPAS airworthiness, there is tight relationship between design and operational aspects within the same regulations, which constitutes another reason to consider this area within the current study. The main emphasis on this second topic shall be on the distinct operational categories in which RPAS can be flown, as other considerations related to aspects such aircraft registration, licencing, and operator approval, would fall outside the scope of this thesis.

The current RPAS regulations in the aforementioned areas which shall be gathered and scrutinised here shall constitute the main corpus of documents to be used in the research on design-airworthiness methods that will be conducted within chapter 8. In that chapter, a process shall be developed to extract from the regulations design criteria so as to then integrate them within design methodologies of generic scope. This is named the DDesign Criteria EXtraction (DECEX) procedure, and it will be expounded in full detail within chapter 8. Taking into account that the findings from the current chapter will serve as a fundamental part of the research on design-airworthiness integration to be developed further along the thesis, particular attention shall be given here to characteristics of the regulations which impact their integration in design workflows.

In view of the above, the present survey constitutes a step towards addressing the developments of the forthcoming chapter 8. However, beyond the use of the standards to be surveyed here as a basis for their integration in design methods, the study developed in the current chapter also seeks to provide insights on the current status, characteristics, and future developments of the RPAS regulatory framework. There are many relevant

conclusions which can be extracted from this analysis, not only from the perspective of the aircraft designer, but also from a purely airworthiness viewpoint. Altogether, the tight relationship between the disciplines of aircraft design and airworthiness supports taking an in-depth look into this area within the scope of the thesis.

3.1. Introduction

A crucial driver towards fully harnessing the potential of RPAS is to achieve their safe integration in non-segregated airspace, which is expected to open up a much wider and promising array of missions, allowing to further leverage the capabilities of these aircraft (22). However, it is also recognised that, to accomplish this purpose in a manner that can maintain the overall level of safety of the aviation system, several aspects related to the safety and risk analysis of these RPAS operations have to be investigated in detail (160; 161; 162).

As a result of previous works that have conducted safety analyses on the integration of RPAS within the airspace, four key dimensions have been identified that are considered crucial towards assimilating RPAS operations in the current aviation paradigm (132). These are stated below along with a set of references which represent a sample of current research in these areas:

- 1) **Airworthiness certification:** (23; 31; 132; 160; 163; 164).
- 2) **Air Traffic Management (ATM) integration:** (160; 162; 165; 166).
- 3) **Interaction with other aircraft, including Detect and Avoid (DAA) considerations:** (162; 165; 166; 167).
- 4) **Flight crew certification:** (23; 31; 168; 169).

All of these dimensions are experiencing a remarkable interest within the fields of academic research, industrial technical developments, and rulemaking activities. This is due to them being key enablers towards expanding the possibilities of RPAS in a safe manner. The investigation presented within this chapter is focused on the first of these dimensions: that of airworthiness certification, as it is the one most tightly related to design aspects.

As it was discussed beforehand in chapter 1, the differences of RPAS when compared to traditional manned aircraft demand the development of new design methodologies which account for these singularities. In a similar vein, when investigating the topic of RPAS legislation, previous authors have suggested that the particularities of RPAS demand a novel regulatory framework tailored to their context, operations, and singular risks. These aspects are expected to result in a markedly distinct paradigm from that of traditional aviation (23), requiring specific methods of study and analysis (161). The differences of these aircraft when compared to conventionally-piloted ones are

anticipated to not only have an impact at the fine level of specific certification requirements, but also on the overall organisation and guiding principles of the regulatory paradigm as a whole.

This line of thought is shared by Aviation Authorities themselves, who have recognised the need to build a novel framework of regulations for RPAS, with specific standards and recommended practices crafted attending to their singularities. Thus, and so as to allow the safe development and expansion of these aircraft in the aviation domain, these Authorities have conducted an outstanding rulemaking work along the past decades so as to lay down this new paradigm. Figure 3-1 represents an overview of recent regulatory milestones related with the main work of international civil Aviation Authorities within the areas of initial airworthiness and operational categories of RPAS, which are the main areas of work within this chapter. This is only a sample of the full regulatory activity that is being carried out, which spans many other diverse areas, and is also being conducted by many entities both at an international and national level. Clearly, this surge in regulatory activity has had an impact in the RPAS paradigm as a whole, which is not only seen in the material produced by the Authorities themselves, but also in previous research works studying various relevant dimensions of the international RPAS legal framework and its evolution, including personnel licensing (23; 168), RPAS registration (168), operator certification and registration (31; 168), integration into non-segregated airspace (160; 162) or privacy (23; 170), amongst other aspects. The evolution of national RPAS regulations has also attracted significant research and discussion, such as in the works of (2; 31; 171).

To guide the development of regulations in the various aviation domains, Aviation Authorities follow rulemaking principles and regulatory guidelines laid out in advance. These include top-level criteria which not only organise the structure of the regulations to be written, but also have an impact in their specific contents (159). To conduct an analysis of particular regulations, it is crucial to keep in mind the overall rulemaking principles which have been employed for the development of standards in the specific domain of research. As mentioned above, and due to the particularities of RPAS, the regulatory area pertaining to these aircraft presents numerous singularities. For instance, one of the main differences of the RPAS framework when compared to the traditional manned aviation one is that there is a much tighter coupling between different regulatory areas in RPAS. Aspects related to initial airworthiness and design appear in many documents alongside operational categories and constraints. The reason for this is that the applicable regulatory category is not only linked to the inherent characteristics of the aircraft, but also to the operational scenario where it is flown. This aspect, which is currently already prescribed in various regulations and standards, was already envisioned in previous works such as those of (161; 172) as one of the potential needs for the development of an airworthiness framework for RPAS. Some other particularities of the RPAS regulatory field will be discussed in section 3.2.

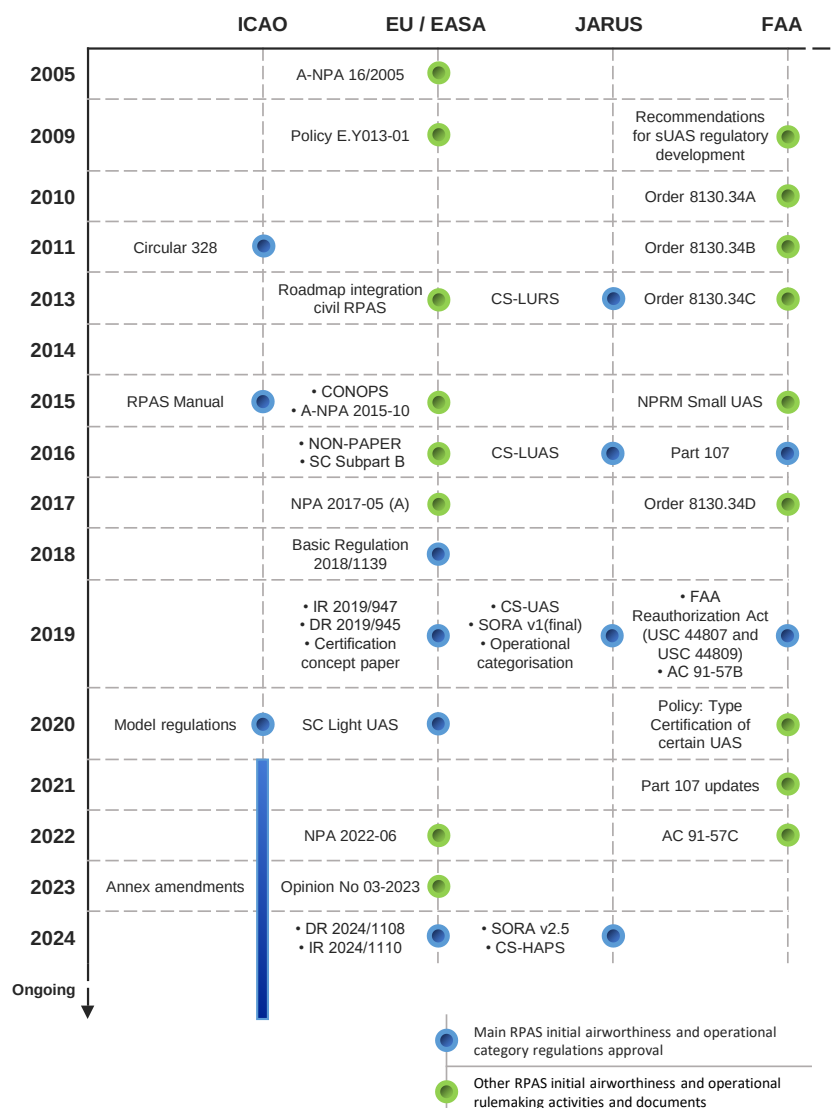


Figure 3-1. Summary of main regulatory highlights in the areas of initial airworthiness and operational categories from civil organisations with marked international influence. EU (European Union), JARUS (Joint Authorities for Rulemaking on Unmanned Systems), A-NPA (Advanced Notice of Proposed Amendment), sUAS (small Unmanned Aircraft Systems), CS (Certification Specifications), LURS (Light Unmanned Rotorcraft Systems), CONOPS (Concept of Operations), NPRM (Notice of Proposed Rulemaking), SC (Special Condition), LUAS (Light Unmanned Aeroplane Systems), IR (Implementing Regulation), DR (Delegated Regulation), SORA (Specific Operations Risk Assessment), USC (United States Code), AC (Advisory Circular), HAPS (High Altitude Platform Systems (HAPS)).

It should be noted that the rulemaking development within the field of RPAS is still ongoing and there are regulatory gaps that have yet to be covered, such as the development of the framework for the certified category within the paradigm of EASA. Furthermore, there are also relevant challenges in the application the currently available standards. As it will be seen further along this chapter, and in spite of recent harmonisation efforts, there are still remarkable differences in the philosophy and content of initial airworthiness regulations, and particularly of certification codes.

Depending on the legal context of the envisioned operation and the regulations applicable therein, there can be a significant variety in the requirements to be considered. This constitutes a significant challenge, as it has been highlighted in other areas of aviation that harmonisation amongst regulatory paradigms is a significant aid in achieving uniform and widespread safety levels (159; 173). Connecting with the topic of design which serves as the main guiding thread of the thesis, this lack of harmonisation also affects the designer, as the airworthiness requirements that must be integrated in the design continuum could be heterogeneous and even conflicting.

Taking into account the overall relevance of airworthiness standards in the domain of RPAS, as well as their tight relationship with the topic of RPA design, this chapter shall conduct a detailed survey on the field of RPAS initial airworthiness regulations. The aim is to cover OBJ.2.1 as laid out in section 1.4, which seeks to conduct a thorough analysis on the topic of current RPA regulations, with a particular focus on aspects related to their potential incorporation in design methods, so as to link with the developments to be conducted later on within chapter 8 concerning design-airworthiness integration in RPA conceptual design. The purpose of the survey is two-fold: to analyse from a broad airworthiness perspective the current status, gaps, and challenges of the initial airworthiness domain in RPAS also accounting for certain operational aspects; and also to evaluate the impact of the characteristics of the regulations in their potential integration within RPA design approaches. Thereby, the analysis developed here attends to both airworthiness and design perspectives, as well as to the overlap between them.

3.1.1. Survey scope

As mentioned beforehand, the field of RPAS regulations is remarkably broad and covers many different dimensions. Thereby, it is fundamental to establish the scope of the survey, aligning it with the main objectives of the chapter and of the thesis overall. The following points highlight the boundaries of the research conducted here:

- With respect to the airworthiness topics to be considered, the focus shall be set on initial airworthiness regulations, which are of particular interest in the initial stages of aircraft design, as seen in previous works (7; 8; 9; 48). It is also noted that the initial sizing phases often deal with aspects relative to the overall vehicle, with more specific considerations being usually considered later on the design continuum, such as those related to structural component design or systems engineering (78; 80; 174). Thereby, among the initial airworthiness requirements, those related to the overall air vehicle shall be the ones of interest in this work, according to the thesis' scope. This further aligns the frame of this survey with the objectives of chapter 8, where the integration of the regulations analysed here in conceptual design methodologies shall be investigated.
- In relation to the previous point, and as anticipated earlier in this section, one of the main peculiarities of the field of RPAS is that initial airworthiness and design

aspects often appear within the same regulations alongside those related to operational categories and restrictions. Therefore, these aspects shall also be included in the review.

- Moving on to the aircraft type, and according to the overall of the thesis, the regulations to be studied shall be the ones focused on fixed-wing aircraft. In those cases where a document covers this kind of RPA along with others, such as rotary-wing ones, the standard shall also be considered here.
- Regarding the regulatory documents themselves, the ones to be studied shall be those produced by the main Authorities with marked international influence in RPAS rulemaking. This is in contrast with previous research, which has mostly focused on national regulations (2; 31; 171), thus constituting one of the main highlights of the research conducted in this chapter. These types of organisations are also usually more relevant to the aircraft designer due to the potential broader applicability of airworthiness aspects integrated in the design continuum. The main entities considered here are as follows: ICAO, EASA and the FAA. Documents from the Joint Authorities for Rulemaking on Unmanned Systems (JARUS) shall also be taken into account, due to their tight relationship and mutual influence with EASA. Furthermore, documents from the North Atlantic Treaty Organization (NATO) have been included due to their relevance in the certification of various existing RPAS and their synergy with civil documents and standards.

3.1.2. Contents overview and structure

Here, an outline is given on the different sections of this chapter as well as the connections among them. As mentioned beforehand, the analysis of particular aspects from regulatory documents should be conducted attending to the high-level criteria governing the overall paradigm. Taking this into account, section 3.2 expounds the theoretical background on the current state and main characteristics of the international RPAS regulatory frame. This serves to outline some of the challenges that are faced by the RPAS designer and operator, which will also be considered through the survey within this chapter. In section 3.3, some previous works that have conducted reviews of RPAS regulatory material are evaluated, and research gaps are identified. This allows to highlight that the area of international initial airworthiness regulations would benefit from an updated survey, considering that previous ones on this domain were conducted some time ago, and the regulatory framework has evolved significantly.

Moving on to section 3.4, it proposes the main criteria and process of the survey to be developed here. This includes the definition of a set of characteristics for the review of regulatory documents, which have been crafted considering both airworthiness and design considerations. These allow to assess several aspects which are focal to the review and to the objectives of the thesis overall, such as the current regulatory gaps in terms of RPA design airworthiness criteria, and also characteristics related to the integration of

regulations in design methodologies. The survey itself is conducted in section 3.5, covering two steps at different levels of granularity. The first stage shall perform a broad analysis on initial airworthiness and operations regulations, whereas the second will focus on documents whose characteristics make them more useful for their integration in initial design approaches for RPA. The findings from this analysis are wrapped up in the conclusions section 3.6, and will also have an influence downstream towards the research on design-airworthiness integration methods for RPAS within chapter 8 of the thesis. Two particular aspects of the present chapter shall be directly employed therein. Firstly, the criteria used here for the review of airworthiness documents shall also be leveraged in the DECEX procedure to select the most promising regulations for design-airworthiness integration, and they will also be employed to evaluate particular regulatory requirements and the feasibility of generating design specifications from them. Secondly, the documents and findings of the survey itself shall serve as the main source of RPAS airworthiness requirements to be considered in the DECEX procedure. Figure 3-2 provides an illustration of the structure of this chapter, as well as its connections with chapter 8 of the thesis.

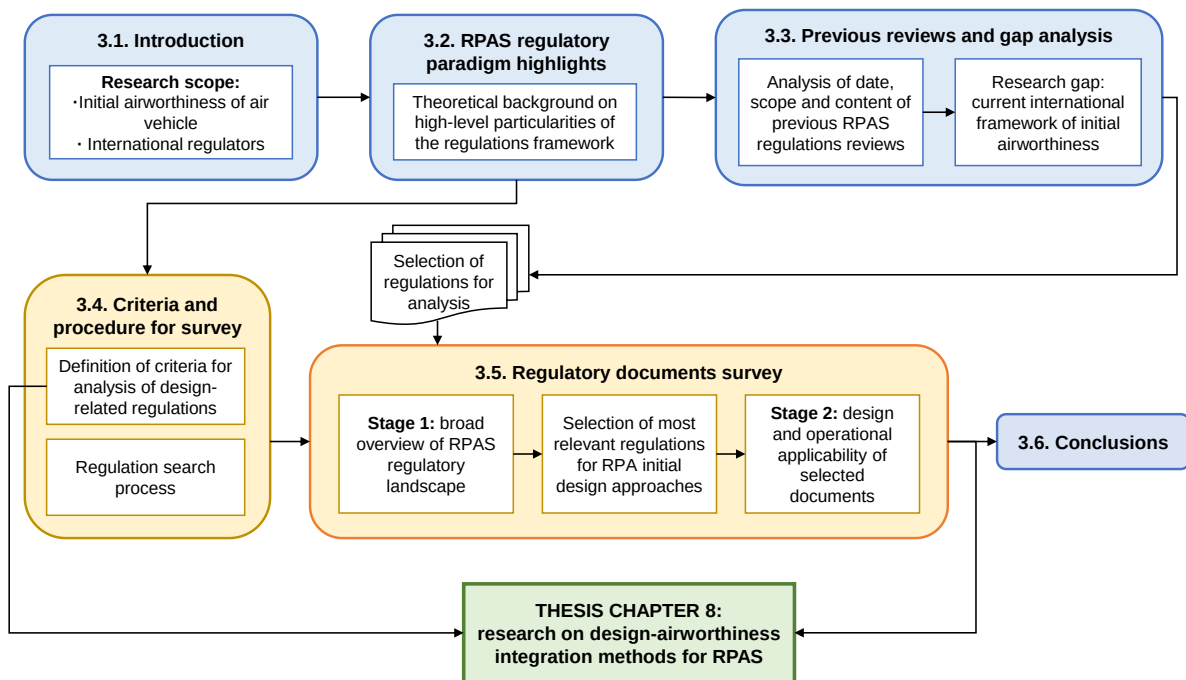


Figure 3-2. Outline of the main sections of the present chapter, detailing the connections among them, and also the elements that will be directly employed in the research conducted within chapter 8 of the thesis.

3.2. RPAS initial airworthiness and operations regulatory paradigm highlights

As commented in the introduction, the particularities of RPAS when compared to aircraft which are piloted on-board demand a novel regulatory paradigm with respect to that of traditional manned aviation (23). This new framework is expected to be tailored attending to the singularities of RPAS, resulting in distinct high-level principles which then flow downstream and affect the characteristics of the specific regulatory documents developed within this paradigm. Therefore, the analysis of particular standards in this domain would firstly benefit from scrutinising the overall peculiarities of the RPAS regulatory framework as a whole.

A brief account is given below of those aspects within the RPAS regulatory paradigm which are more relevant within the scope of this work:

- **Risk-based and operations-centric approach:** the concept of developing regulations in accordance with the proportionality of risk of the object for which these rules are being developed is not new and has been present in manned aviation for a long time (175). This idea is supported by ICAO among their good regulatory practices, stating that: *“Regulations should be used only when their necessity is demonstrated and should be proportionate to the problems identified so that the costs of compliance are minimized by pursuing the most cost-effective solution”* (175). In the particular field of RPAS, along the process of development of the successive regulatory initiatives, there has been a shift from a traditional viewpoint, which is “aircraft-centric”, to an “operation-centric” approach, which is based on an analysis of the risks resulting from the combined consideration of the aircraft and its operation—in line with previous research in this area (161). For instance, in the framework of EASA, different operational categories (open, specific and certified) have been defined, where regulatory requirements increase in correlation with risk—from minimal regulatory oversight in the first case, to a very similar model to manned aircraft in the third, in which initial airworthiness and operators are certified, amongst other aspects (176; 177). It has been stated that this approach, in the particular case of RPAS, seeks to avoid placing disproportionate restrictions and difficulties in the regulatory compliance process for low-risk operations (23). Considering the ubiquity of small RPAS, and the role that Small and Medium Enterprises (SMEs) are expected to have in this commercial area (30), stringent requirements could result in excessive regulatory hurdles which could hinder the development of this field.
- **Tight coupling between initial airworthiness and operational considerations:** in relation to the previous point, one of the most innovative aspects of current RPAS regulations is that a very tight coupling between airworthiness and operation considerations can be seen, with aspects related to

these areas often appearing side-to-side in the same documents (23). This is coherent with the risk-based approach, which considers aspects inherent to the aircraft in combination with those of the operational scenario, often with both aspects in combination determining the regulations that apply to the aircraft under consideration. Previous research in the area of RPAS safety also highlighted the possibility of both operational and design aspects being considered concurrently to arrive at an overall risk level, which could then determine the requirements to be imposed (161). This aspect has motivated that the survey to be conducted in this chapter not only covers initial airworthiness documents, but also those related to operational categories and constraints, as commented in the scope exposition, since both dimensions often appear in an indivisible manner in the same documents.

- **Performance-based approach to airworthiness codes:** the reorganisation and change in spirit of the Part/CS-23 regulations (178) has had a notable impact in the field of RPAS regulations. This activity sought to regulate through “objective oriented” requirements, seeking to provide flexibility to applicants in the way that they demonstrate compliance with the regulation specifications, and at the same time intending to reduce both regulatory time and costs, both for the industry and for the regulator (178). The result is that the requirements provided in the codes have a lower level of detail when specifying the aspects with which the design must comply, and are less prescriptive in nature. This is in contrast to the traditional “prescriptive approach”, which is still maintained in many parts of the aviation regulations, particularly in standards and codes dealing with higher-risk aspects or aircraft, such as the Part/CS-25 regulations. This dichotomy is tightly connected with the concept of “level of specificity” that will be commented further below in subsection 3.4.1, and which is focal for the survey to be conducted in this chapter. To complement the requirements within the performance-based codes, which are less specific when following this paradigm, the applicant can opt to demonstrate compliance with them through use of Acceptable Means of Compliance (AMC) and Guidance Material (GM), which, in the case of the reorganisation of manned aircraft regulations, can include references to previous versions of the regulations and also to consensus standards. These other references shall usually present a higher level of detail, which the applicant can use to complement the broader guidelines of the main requirements. This performance-based approach has been supported in the area of RPAS in works previous to its formal implementation, such as that of (2). This concept has been implemented, for instance, in the CS-UAS by JARUS (179), where the specific requirements that the designer can find outside the main document are called Airworthiness Design Standards (ADS). However, contrary to the Part/CS-23 approach, in this case there is no clear correspondence between each requirement of the regulation’s main corpus and the corresponding ADS recognised by the Authority. This can be considered as an additional challenge to establish the initial

certification basis and to guarantee certifiability assurance in advance to making specific consultations with the Authority.

Aise from the aforementioned high-level regulatory criteria, it is also relevant to reference the current harmonisation status of the RPAS regulations domain. As mentioned in the introduction, it is known that harmonisation amongst regulatory paradigms is a significant aid in achieving uniform and widespread safety levels (159; 173). This is also the case in the field of RPAS, where there have been remarkable harmonisation efforts, particularly in the past few years. Furthermore, regulatory alignment is also relevant from a design standpoint, as will be seen in further detail in section 8.2.

Before moving forward, it should be noted that regulatory harmonisation can be evaluated at different levels of granularity: for instance, it can be analysed at an international level (harmonisation between EASA and FAA) or, rather, at a national level within a certain context (for example, harmonisation between applicable regulations in European Union (EU) member states). Regulatory alignment presents a particular series of challenges, with many possible factors contributing to heterogeneity, some of which are not directly linked to aviation technical aspects. Some of these may include the differing philosophies of each regulator, the development of the market in each country, previous experience with the technology to be regulated, geographical and urban aspects, and even sociopolitical factors that affect the regulatory development (31). A particular case of interest can be seen in the EU region, as the scenario has changed significantly in the past few years. Before the year 2018, according to the previous EASA Basic Regulation (216/2008), EASA only had legal remit in RPAS over 150 kg, and the rest of the cases fell under the scope of the regulations of each Member State NAA. During this time, as previous research pointed out (2; 31), there were many discrepancies amongst the NAA regulations in the EU region, leading to a paradigm in clear need of harmonisation. One of the main premises of the EU is the free circulation of people and goods within the context of the European Single Market; thereby, it was seen that in order to foster the development of RPAS following the premises of the EU, a harmonised approach through the use of Community Law was necessary. The main change came with the update to the EASA Basic Regulation in 2018 (2018/1139), which established that all RPAS operations, irrespective of weight, would fall under the unified scope of the EASA, only leaving state aircraft and operations within the scope of NAA regulations as well as similar concepts. From this point onward, EASA has published numerous regulations, as will be seen in further detail in section 3.5, which nowadays provide a uniform and harmonised paradigm within the majority of RPAS operations for the EU. Thereby, it can be considered that the update to the Basic Regulation was a fundamental step that has resulted in the harmonisation of regulations in the EU for the majority of RPAS operations.

However, as anticipated in the introduction, it will be seen that, when comparing the EU regulatory paradigm to that of the FAA, there are significant differences both in the main guiding principles of the regulations as well as within the regulatory material itself. These

heterogeneous aspects shall be analysed in detail in section 3.5. Thereby, it can be seen that in the international scenario, there is still work to be conducted towards harmonisation. Furthermore, outside the scope of the EU, other national regulations might present significant differences, as evaluated in the previous works of (2; 31; 171), including the information of countries such as China, India and Malaysia, amongst many others. As the scope of the investigation conducted in this chapter is focused on the main international civil entities as laid out in subsection 3.1.1, an analysis of further regulatory heterogeneity would be outside the scope of this research. In any case, it is clear that achieving regulatory harmonisation across different jurisdictions is a key issue towards RPAS certification and design, and in view of the trends followed in recent years, it can be argued that these aspects will continue to develop in the near future. In view of the relevance of this matter, it shall be taken into account along the analysis developed in the survey of this chapter, so as to discuss any current harmonisation gaps and hurdles within the scope of the review.

Finally, it should also be noted that the RPAS regulatory paradigm is still not fully developed, as various areas of regulation are still in progress, such as the development of the certified category in the EASA paradigm. Thereby, the analysis conducted along this chapter would require to be updated alongside any changes in the regulations that occur in the future.

3.3. Previous reviews of RPAS regulations and research gap

Since one of the main objectives of this thesis is to conduct an up-to-date analysis of RPAS regulations in relation with the main topics of the overall research, firstly, an analysis is conducted of previous works that have performed similar studies—that is, previous research studies that have conducted surveys of RPAS regulations in different topical areas. Before moving forward, it is highlighted that section 8.3 will contain a distinct state-of-the-art analysis of previous research, which shall be focused on the domain of design-airworthiness integration. In contrast, the emphasis here is on previous investigations analysing RPAS regulations, irrespective of whether the works have evaluated aspects of integration in design methods, or even if they have analysed regulations dealing with design aspects altogether. In spite of the scope of both state-of-the-art analyses being different, on the other hand they are topically related. Therefore, a few references appear in both of them, albeit the analyses conducted on regarding these investigations is different in each case.

Searching within the open literature and also in textbooks related to the field, various works have been found within the scope of this state-of-the-art analysis. These have been compiled in Table 3-1, where their main characteristics are summarised and compared. The following text provides a brief overview on the main features and overall trends of these previous research efforts.

Table 3-1. State-of-the-art overview of surveys and analyses on RPAS regulations, and comparison with the survey conducted in this chapter.

Reference	Year	Regulatory Focus	Topical Focus	Analysed Characteristics and Parameters
Dalamagkidis et al. (163)	2008	Main international RPAS framework and certain National regulations	Rulemaking activities, airworthiness certificates and RPAS classifications	Possible classifications of RPAS towards certification and potential regulatory road map. Parameters include RPAS mass and flight altitude, minimum time between ground impact accidents, etc.
Cuerno-Rejado, Martínez-Val (132)	2011	International civil and military regulations: EASA, FAA and other	Airworthiness and design: focus on impact energy and load requirements	Practical evaluation of applicability of manned aircraft codes using impact energy criterion. Parameters include impact kinetic energy, gust load factor, structural weight, etc.
Valavanis, Vachtsevanos (2)	2015	EU National RPAS regulations	Technical and operational requirements	Comparison of restrictions to evaluate harmonisation challenges and perspectives. Parameters include MTOW limitations and LOS conditions per regulation, number of operators and manufacturers per region, etc.
Stöcker et al. (31)	2017	Worldwide National RPAS regulations	Technical, operational and administrative requirements	Applicability and main limitations of regulations within selected topics. Parameters include MTOW limitations, distance to aerodromes, distance to people, LOS conditions, etc.
Masutti and Tomasello (23)	2018	International civil regulations, mainly ICAO, EASA and FAA	Varied topics: airworthiness, security, personnel licensing, etc.	Air Law perspective. Scope of regulations, main topics, applicability, etc. Parameters include MTOW limitations, mission radius, probability of failure, etc.
Bassi (170)	2019	EU/EASA civil framework	Privacy, cybersecurity and remote identification	Air Law perspective. Competences of the organisations and open issues. Parameters include regulations and articles related with security, liability, privacy, remote identification, etc.
Srivastava et al. (171)	2020	Worldwide National RPAS regulations	Operations, registration, licensing, data protection and privacy	Operational restrictions and requirements with respect to the analysed topics. Parameters include MTOM limitations, maximum height, lateral distance, etc.
Xu et al. (180)	2020	Worldwide National RPAS regulations	Operations, airspace design and ATM for low altitude operations	Operational restrictions, ATM technologies and airspace architectures. Parameters include maximum flight height, geo-fencing volume characteristics, etc.
Karyotakis et al. (160)	2021	EU and FAA civil paradigms for advanced operations	Airspace integration and ATM for RPAS in relation to specific operations	Comparison of the requirements for advanced/specific operations in both frameworks. Parameters include RPAS mass and height, maximum dimension of RPA, impact kinetic energy, etc.
Alamouri et al. (181)	2021	EU/EASA civil regulations	Rulemaking activities, technical properties, operational prospects and risk assessment approach	Operational category applicability and application of the SORA methodology. Impact of regulations on RPAS use and economic potential. Parameters include RPAS mass and height, maximum dimension of RPA, ground risk class, etc.
Janke, de Haag (168)	2022	EU/EASA civil framework	Personnel licensing and RPAS registration	Requirements towards personnel licensing and registration marks for operation categories. Parameters include EASA open subcategories, no. of operators for specific operations, etc.
This research	2024	International civil and military regulations: ICAO, EASA, FAA, JARUS, NATO	Airworthiness aspects related to aircraft (conceptual) design	Airworthiness aspects and design considerations affecting the potential integration and influence of requirements in design methods. Parameters include document regulatory tier, topical focus of regulations, level of specificity, scope, RPA MTOM, etc.

It can be seen that the field of RPAS airworthiness has attracted significant research effort in recent times, as mentioned previously in the introduction. Each of the surveys that has been found in the literature has analysed different regulatory areas and topics, which is according to the dynamic evolution of regulations in all of these areas. With respect to the Authorities object of study, it is seen that there has been significant effort in studying national regulations in previous research (2; 31). However, few works have analysed and compared the regulations of various Regulators with international influence. Thereby, the international scope of the research conducted in this chapter would constitute one of the highlights of this thesis.

With respect to the areas of initial airworthiness and design, only two previous works, those of (23; 132), have focused on these areas. However, taking into account the regulatory changes since the years in which those works were conducted, as seen in Figure 3-1, a significant research gap can be seen in this area, which this work seeks to cover. Furthermore, the aforementioned two works have integrated requirements from the airworthiness standards within RPA design approaches, which is why they will also be analysed from this perspective in section 8.3. When compared to those investigations, one of the novel contributions of the survey presented in this chapter is the analysis of the regulations attending to particular characteristics that deal with the possibilities of integrating them within design methodologies. These features will be defined in subsection 3.4.1, and they shall also be leveraged in the investigation of design-airworthiness integration approaches for RPA within chapter 8 of the thesis, as mentioned beforehand.

In addition, previous works identified in this section have not considered military codes. Therefore, a further research gap is sought to be covered in this research by incorporating NATO standards, which are military airworthiness codes within the international domain.

3.4. Criteria and procedure employed in the survey

As mentioned in the introduction to this chapter, its main objective is to perform a survey on initial airworthiness documents for RPAS, analysing their airworthiness and design-related characteristics. In particular, features related to the possibilities of extracting design-related requirements for their incorporation in aircraft sizing methodologies shall be emphasised, since this connects with the purpose of chapter 8 of investigating design-airworthiness integration methods for RPA, where the corpus of regulations analysed in section 3.5 of the current chapter will also be employed.

In order to achieve the aforementioned objective, a set of dimensions that are to be analysed in the review of the different documents should be defined first, so as to allow to compare them and to detect potential challenges and gaps both in the areas of airworthiness and design within the regulatory paradigm of RPAS. This process of defining the characteristics to be evaluated when analysing the regulations covered by

the survey is covered below in subsection 3.4.1. Furthermore, the search process for finding the regulatory documents is also outlined below.

3.4.1. Definition of characteristics for the review of design-related airworthiness regulations

As it was commented previously, there will be two stages of the regulations survey. In the first, the broader scope of documents related to the initial airworthiness of RPAS shall be analysed, whereas the second stage will focus on those that can be more promising towards the integration of airworthiness requirements within the first stages of RPA conceptual design. These shall constitute the main corpus of documents to be considered in chapter 8 for the investigation of design-airworthiness integration methods for RPAS, and in particular, in relation to the DECEX procedure to be developed therein.

The set of characteristics of the regulations to be evaluated in the survey shall be defined in the current subsection. They will be crafted attending to the objectives, scope and priorities of the survey, following a similar approach to that of previous regulatory reviews such as those of (2; 31; 171). In the case of the present research, the characteristics should be relevant from the viewpoints of both airworthiness and design, since these two disciplines are at the forefront of the investigation conducted in this chapter. The characteristics should also aid in selecting those documents which have features that might render them more useful towards their incorporation in initial design approaches for RPA, as this selection process is fundamental towards narrowing down the documents to be analysed in more detail within the second stage of the survey. Furthermore, aside from their use in the current survey, the characteristics defined here will also be leveraged in chapter 8, particularly within the DECEX procedure. As anticipated beforehand, its purpose shall be to extract design criteria from regulations for their integration in RPA design approaches. As the set of characteristics to be defined in the current subsection evaluate, among other aspects, those features of the regulations which might aid their incorporation in design methods, they also match with the purpose of the DECEX procedure.

In contrast with previous works which have also defined their own set of dimensions for regulation assessment, one of the novel contributions of this research is that the criteria have been selected considering both airworthiness aspects and design considerations affecting their potential integration and influence in design methodologies, which were aspects not covered by previous regulatory reviews, as discussed in section 3.3. It should be noted that some of these criteria can be evaluated not only at the level of full regulations, but also at a finer level of granularity for singular requirements. This aspect shall be essential later on in the thesis towards the use of these characteristics within the DECEX procedure, since it evaluates not only regulatory documents as a whole, but also specific requirements, as it will be thoroughly expounded within chapter 8.

The set of characteristics for the assessment of design-related airworthiness documents that have been crafted for this survey are the following:

(a) Level of Regulatory Document Tier (LRD Tier)

Usually, regulators organise the taxonomy of their documents according to “levels of regulatory material”, such as EASA, which has a hierarchical structure of its regulations. For instance, the Basic Regulation is at a higher hierarchical position than the CS codes, and so on. In this work, documents from entities with differing criteria to organise their material are being studied concurrently, which constitutes a challenge to consider unified regulatory document levels. Therefore, this LRD Tier concept will be applied in a broad sense, allocating the same Tier to documents with a similar nature in their breadth and scope. Tier 1 is for high-level documents laying out essential requirements and covering a broad scope, including implementing regulations. At the same time, their level of depth and detail is usually low, as the intention is to provide general governing guidelines and not specific criteria. For example, the EASA Basic Regulations, in the Essential Requirements for Airworthiness, lay out general qualitative criteria for structures and materials; however, one must consult the lower-tier CS codes to find specific quantitative limit load factor values (159). Tier 2 is for more detailed documents giving specific provisions for aspects that are not covered within Tier 1 ones, in the vein of Certification Specifications (e.g., Part/CS-23). Tier 3 documents have more detail and focus, such as FAA Advisory Circulars (ACs), and EASA AMC and GM. Tier 4 is reserved for consensus standards and similar documents.

(b) Legal applicability

This concept refers to the nature of the document with respect to its legally-binding status or otherwise. This dimension is not exclusively dependent on the document itself but also on the scope of use of the document that is considered. This can depend on many other aspects, such as the country where the RPAS operation is expected to take place, and also on whether the civil or military paradigm is being considered. For example, the FAR regulations are legally binding in the USA, but they are not in other countries, unless the particular State has adopted the FAR regulations through a legal process in the State’s Official Legislation Publication. Another case is exemplified through the NATO Standards, which have legal remit in military operations of Signatory States to the NATO Treatment. For instance, the NATO Standard Allied Engineering Publication (AEP) AEP-4671, also known as Standardization Agreement (STANAG) STANAG 4671, was formally adopted in Spain through a publication in the Official Journal of Defence (182). Within this work, and in order to establish a uniform criterion when using this legal applicability concept to assess the regulations to be analysed within the survey, this shall be evaluated within the main civil framework related to the application scope of each regulation. For instance, the legal applicability of FAA Part 107 is evaluated for the USA, whereas the legal applicability for EASA regulations is assessed for the EU Member States.

(c) Topical focus

This dimension evaluates in broad terms the main subjects covered by the document. These can be the topics of initial airworthiness, continuing airworthiness, or operations, among others.

(d) Level of specificity

This concept relates to the level of detail provided within the requirements written down in the regulation, and it is crucial from both the standpoints of airworthiness and design.

Attending to the airworthiness perspective, it is tightly linked with the dichotomy between prescriptive regulations and performance-based regulations as expounded on section 3.2. It was stated that, following the performance-based approach, the requirements provided in the main codes usually have a lower level of detail, particularly when compared to traditional regulations that follow a prescriptive approach.

From the perspective of design, this concept of level of specificity is linked to the ease of generating design specifications from the regulatory requirements. For instance, a paragraph in the code stating that the stalling speed may not exceed 83 km/h provides a high level of specificity, since it establishes a quantitative value that can be immediately translated to a particular design requirement. At the same time, it constitutes a prescriptive requirement which gives little margin of negotiation, thus it must be complied with by the applicant. On the other hand, a paragraph stating that the aircraft should have stability and control characteristics that allow for safe operation would not allow a direct and unequivocal derivation of a design specification, owing to its more qualitative nature. In fact, the consideration of this level of specificity characteristic here has been largely due to the low detail of certain certification requirements having been considered as one of the main hurdles towards airworthiness-design integration, as supported by the work of (49). In contrast, this lower level of detail allows the applicant more room for establishing the ways in which to comply with the requirement, which other viewpoints consider as a positive feature.

In view of the above, the implications of the level of specificity from both airworthiness and design standpoints are tightly interlinked. As seen beforehand, there are varying viewpoints on the potential advantages and disadvantages of both kinds of requirements, which shall be discussed along the survey conducted within this chapter. The implications of the level of specificity on the integration of airworthiness requirements within design methods, and its impact on the design space, shall be discussed in more detail within section 8.2, and this characteristic will be fundamental in the use of the DECEX procedure as it will be developed in section 8.4.

Three distinct levels of specificity are considered. Table 3-2 provides three examples on the allocation of specificity levels to example regulation excerpts from the field of RPAS.

- 1) **Low:** when only general qualitative criteria are given.
- 2) **Medium:** where no detailed quantitative specifications are provided but more specific aspects to be taken into account or calculated by the applicant are provided.
- 3) **High:** where specific values or limits are given.

(e) Streamlined or ad-hoc requirements

Streamlined procedures are those that are relatively straightforward in that the requirements to comply with are mostly laid out in advance. This is usually the case of classical certification specification codes. However, in the field of RPAS, there are cases, mostly pertaining to specific category operations (177), where requirements or necessary mitigations to be implemented by the applicant are laid out depending on the result of a prior operational risk assessment. An example is the Specific Operations Risk Assessment (SORA) methodology by JARUS, where the number of barriers, as well as their integrity, depend on the result of a preceding operational risk assessment. In these cases, the requirements are a function of the outputs of this risk assessment study; therefore, depending on the case of application, the set of conditions that must be complied with are different. These are considered ad-hoc procedures, and they do not provide a pre-established certification basis; rather, it is dependent both on the aircraft and the operation to be conducted. From a design perspective, and particularly when considering the first design stages, these approaches could hinder the integration of requirements within design methodologies due to various reasons:

- 1) As the results of the risk assessment are dependent on the operational scenario, different operations, even with the same aircraft, might demand differing requirements. Furthermore, not all possible operational scenarios might be envisioned in the first stages of the design project.
- 2) The safety assessment might demand to analyse certain aspects of the aircraft that might not be known at the first stages of the design, such as systems architecture or reliability estimations. This is linked with the evolution of the aircraft concept through the design continuum and the fact that certain methodologies and disciplines of analysis require a more detailed definition of the aircraft to perform their analyses, as discussed in subsection 2.1.2. This is also why the application of more advanced risk analysis techniques is usually left for later design stages, as it will be commented in detail later on within section 8.2.

The case- by-case approach of determining the certification basis for each combination of aircraft and operational scenario can complicate the definition and integration of a unique set of certification aspects in a design process. Some other advantages and disadvantages of this kind of ad-hoc approach in the domain of RPAS airworthiness have been discussed in previous research (183).

Table 3-2. Examples of the level of specificity concept applied to three different requirements within the field of RPAS.

Level of specificity	Example	Rationale
Low	<i>"CS-UAS.2115 Take-Off and minimum performance</i> <i>(a) The applicant must determine the UA minimum performance required for take-off,</i> <i>(b) If the most critical fight phase is other than take-off, the applicant in addition to (a) must determine the UA minimum performance for this fight phase."</i>	According to the criteria given in this subsection, this requirement only establishes broad aspects that the applicant must determine, but no specific guidance is given on what aspects of performance are required, nor is any numerical constraint provided
Medium	<i>"CS-LUAS.53 Flight Performance</i> <i>The following information must be determined and provided in the approved Flight Manual:</i> <i>(a) In take-off configuration at maximum weight within the operational flight envelope established for take-off:</i> <i>(1) The rotation speed VR, except for catapult assisted or rocket assisted take-off and hand launched RPA</i> <i>(2) The obstacle clearance height, agreed by the authority</i> <i>(3) The distance required to take-off and climb to the obstacle clearance height</i> <i>(4) The minimum speed at the obstacle clearance height."</i>	More detail is provided than in the previous case regarding the variables and parameters that the applicant must determine, albeit no numerical constraint is prescribed
High	<i>"USAR.65 Climb: All Engines Operating</i> <i>(a) Each UA must have a steady gradient of climb at sea level of at least 5% with:</i> <i>(1) Not more than maximum continuous power on each engine;</i> <i>(2) The landing gear retracted (if such a configuration is designed);</i> <i>(3) The wing faps in the take-off position(s); and</i> <i>(4) A climb speed not less than the greater of 1.1 VMC and 1.2 VS1 for multi-engine UA and not less than 1.2 VS1 for single-engine UA."</i>	In this case, not only are requirements prescribed in relation to specific variables, but quantitative values are also provided by the regulation

There may be some alternative ways to comply with the safety evaluation requirements depending on the regulatory paradigm, such as through the adherence to standard scenarios, or by acquiring a Light UAS Operator Certificate (LUC) in the EASA paradigm. However, these options can heavily restrict the type of aircraft and operations, and they can often be outside the grasp of the designer, so they are considered to be outside the scope of this investigation.

(f) Scope

This dimension evaluates the boundaries of the regulation regarding aircraft type (fixed-wing, rotary-wing, hybrid) and the operational category (open, specific, certified).

3.4.2. RPAS Regulatory Document Search Process

An overview of the search process of the RPAS regulatory documents to be included in the survey is outlined here. These documents shall be selected according to the scope of the research, which, as it has been anticipated and as it will be seen in section 3.5, focuses on entities with marked international influence in the rulemaking paradigm—more specifically, ICAO, EASA, FAA, JARUS and NATO—representing both the civil and military domains. Other aspects of the main scope to be considered are the focus on initial airworthiness aspects and also on fixed-wing aircraft, as laid out in subsection 3.1.1.

Previous surveys of RPAS regulations employed three distinct approaches to the document search process:

- 1) An in-depth analysis of the original sources of information, which are mainly the websites of the different Authorities, as performed for instance in (23; 132).
- 2) The use of pre-compiled lists and overviews of regulations laid out by previous works or by recognised RPAS organisations, such as in (31).
- 3) A combined approach, as seen in (171).

The first procedure is less streamlined as it requires navigation in the specific websites of the different Authorities, which usually employ quite different structures to their contents and documents, but it provides certainty that the documents are official (of particular interest to the aircraft designer) and current (which is important in view of the rapid evolution of the regulatory landscape). The second approach is more streamlined and allows for greater reproducibility, but the sources of information are not the original ones. Furthermore, upon checking many of the pre-compiled lists cited in previous research, these are no longer available, which also affects the third approach on the part of the databases. Thereby, the first procedure was selected for the current work. In order to search for relevant documents within each entity's website, two approaches were followed:

- 1) The search engines of the entities' websites have been used with keywords related to the area of study, including, amongst others: 'RPA', 'RPAS', 'UAV', 'UAS', 'drone', 'unmanned aircraft', etc. The search results were then sorted so as to keep those related to the scope of the study.
- 2) Applying previous knowledge of the websites' site map and of the hierarchy and organisation of documents from different entities (159; 184), the areas related to RPAS regulations and rulemaking processes were examined so as to find documents relevant to this research.

These two methods complement each other, as some documents, such as the EASA SC-RPAS.SubPartB-01, could not be found directly with the second procedure within the Unmanned Aircraft area of the website, but were found through the search engine. Rulemaking documents such as Terms of Reference (ToR) and Notices of Proposed Amendments (NPAs) were found through the second method by following the thread of relationships of these documents with each other. Overall, this search process yielded an extensive database of documents, which will be analysed in section 3.5 within the survey.

3.5. Survey of RPAS regulations on initial airworthiness and operational restrictions

This section contains the two-stage survey mentioned in the introduction. In the first stage, a broader set of stakeholders and regulations are reviewed to provide a wide outline of the current RPAS regulatory landscape related to initial airworthiness. Here, the criteria defined in subsection 3.4.1 are employed to analyse and compare the relevant documents. This step is more focused in initial airworthiness from a general perspective, but some design-related considerations will also be discussed, mainly through the review characteristics as defined in subsection 3.4.1. In view of the results of this stage, and employing the aforementioned criteria for review, only the most promising documents from a design standpoint are kept for the second stage in order to conduct a further analysis. This one shall focus on their applicability ranges and criteria, as related to design and operational restrictions. Therefore, this second stage shall be more focused on design aspects, and one of the main purposes is to detect potential gaps in areas that are still not covered by the applicability of the different documents. In this way, the combination of both stages covers the main topical areas of the research presented in this chapter.

In addition to the scope of the work, as established in subsection 3.1.1, two additional aspects delimiting the survey are commented here:

- Owing to the bibliographic sources available during the research, access to regulatory documents has been limited to those that are publicly available in the open domain.

- Albeit some regulations allow for waivers or exemptions to certain requirements, these particular cases, which have to be evaluated in a case-by-case basis for each design and operational scenario, have not been included in this review.

The written discussion in both stages of the review shall be more focused in expounding the context and general aspects of the documents that shall be analysed, whereas the main results of evaluating the different criteria for the review of the documents are contained within Table 3-3 for the first stage of the review, and in Table 3-4 for the second one. The main text shall also develop the foremost aspects of discussion and comparison between the regulations attending to the aforementioned criteria.

3.5.1. Stage 1: Broad Review of Current Regulatory Landscape

The following text offers some context and general comments on the regulatory paradigm related to the initial airworthiness documents of each entity, with the results complementing this exposition being present in summarised form in Table 3-3, which includes the outputs from analysing the characteristics laid out in subsection 3.4.1 for each of the documents.

(a) ICAO

It could be considered that the first deliverable of ICAO with respect to RPAS rulemaking was Circular 328 (185), stating general policy and objectives for rulemaking activities and considerations for ICAO Standards and Recommended Practices (SARPs) amendments. This document, as is usual of ICAO Circulars, has a broad scope and is of high-level nature. The next main deliverable could be considered to be the Manual on Remotely Piloted Aircraft Systems (186), which is more detailed than the Circular, while still remaining at a high level, as is usually the case of this type of ICAO document, which seeks to provide guidance to Contracting States on technical and operational issues. It should be noted that the airworthiness paradigm proposed here is the traditional one consisting of Type Certificates, Certificates of Airworthiness and approved organisations for design and production. In both cases, no specific design-related provisions are provided; so, these documents are not particularly suited to direct integration in design methodologies, albeit having great importance in the international initial airworthiness paradigm of RPAS and ICAO further developments, thus they are included here.

Even though before the publication of the RPAS Manual some Chicago Convention Annexes had already been amended, including some relatively straightforward aspects related to RPAS (such as the amendment of Annex 13, which included a new definition of “accident” applicable to RPAS), it was from the time of publishing of the RPAS Manual onward when ICAO started the very ambitious task of amending the Chicago Convention Annexes to include more thorough aspects related to RPAS airworthiness and operations. This activity is still ongoing, with some of the key Amendments envisaged for applicability in 2026 (187). Chicago Convention Annexes are documents requiring payment, but some

information was found through other references covering the potential changes such as (23), and also in the ICAO document (187).

Another relevant source of ICAO material is the ICAO UAS Toolkit, the main web page of which can be found in (188). This resource is directed foremost to regulators in the Contracting States, providing the main perspectives and guidelines of ICAO to aid in their rulemaking. Of particular interest are the documents provided in the form of ICAO Model UAS Regulations, issued in 2020, the main purpose of which is to serve as an example and template for Contracting States to develop their own RPAS regulations. These include the following: Part 101 (189), dealing with operations in the open category; Part 102 (189), dealing with operations in the specific category and also other aspects such as operator certification; and Part 149 (190), which tackles organisation approvals. It should be noted that the operational categorisation employed by ICAO has a similar basis to that used by EASA and JARUS (177), as it will be seen later. These model regulations have seldom been the object of academic analysis, so their inclusion can be considered one of the main contributions of this research.

(b) EU/EASA

The development of regulations for the field of RPAS within the EU framework has followed a long process, with many changes in direction in the first stages of the rulemaking progress. This survey focuses on the currently applicable paradigm and documents, which has resulted from a series of rulemaking tasks from 2015 onward. A detailed account on the historical perspective and the previous paradigm can be found in the works of (23; 181).

The current regulatory framework is markedly operations-centric, and the main “hard law” Regulations approved by the EU Commission are the following:

- **Commission IR 2019/947** (191): Focuses on aspects related to rules and procedures for the operation of RPAS, laying out the principles for the three main categories of operations: open, specific and certified. It also covers topics such as remote pilot licensing and instructions related to conducting operational risk assessments for the specific category.
- **Commission DR 2019/945** (192): Deals with the applicable requirements for RPAS in the different categories of operations with respect to manufacturer’s obligations and markings and documentation for commercial RPAS. The Appendix expounds the specific limitations for the classes of RPAS from C0 to C6, mainly intended for open and specific operations.
- **Commission DR 2024/1108** (193) and **IR 2024/1110** (194): These recently approved regulations integrate RPAS aspects within the classical framework of the EU Implementing Regulation for initial airworthiness IR 748/2012, allowing RPAS as well as their equipment and control stations to be included within the

paradigm of type certificates, establishing the certification basis, airworthiness certificates, etc.

While provisions for the open and specific categories are already mostly laid out, the certified category of operations is still under development. As commented in the rulemaking documents (195; 196), detailed certification codes for RPAS such as CS-UAS and CS-Light UAS are expected for 2025. It should be highlighted that the current concept of EASA with respect to the use of CS for RPAS is laid out in (196) and illustrated in Figure 3-2 below. The main idea is that a classical certification code adequate to the type and risk of the RPA will be selected (for instance, CS-23), and the requirements will be complemented with RPAS-specific aspects contained in CS-UAS. On the other hand, for the case of Light UAS, the future CS-Light UAS would contain all the applicable requirements.

Aside from this, currently and until the new CS landscape is established, there are some RPAS special conditions available. In this work, due to their relation to the airframe of fixed-wing aircraft and the research scope in general, SC-RPAS.SubPartB-01 (197) and SC Light- UAS for Medium and High Risk (198) have been included, and their main characteristics can be seen in Table 3-3. It has not been seen that these references were reconsidered in previous works; therefore, their consideration here would constitute one of the novel aspects of this survey.

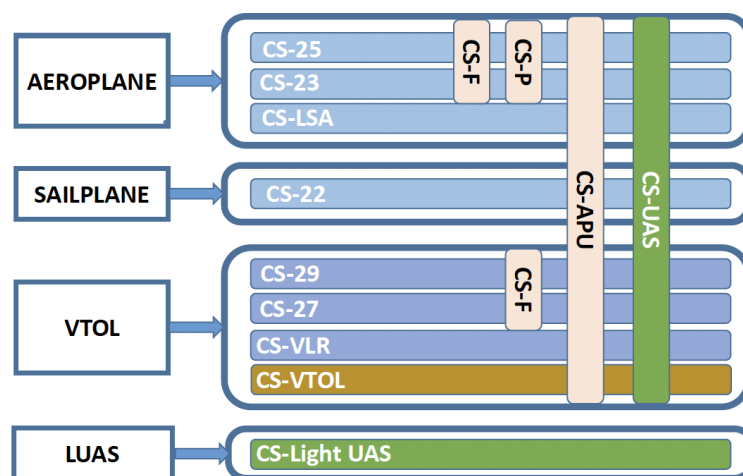


Figure 3-3. Representations of the organisation and interrelations amongst CS codes within the future EASA RPAS framework. Figure adapted from (196).

(c) USA/FAA

Within the FAA framework, there are also different applicable regulations depending on the characteristics of the operation and of the air vehicle. Albeit the categories of operation of open, specific and certified are not employed here, some parallels can be drawn. The main applicable regulations and paradigms are briefly commented below:

- **Part 107 (199):** This is the main regulation in the FAA paradigm for flying RPAS below 55lb with commercial and professional purposes and is also an option for public operations that fall within the restrictions of this regulation. It lays out requirements with respect to pilot licensing, operational restrictions, registration of aircraft, etc. Four different operational categories are established for operations over human beings, with differing requirements and restrictions with respect to the aircraft and operation characteristics. Waivers can be requested for many of the limitations, which are evaluated by the FAA on a case-by-case basis.
- **49 USC 44809 Exception for limited recreational operations of unmanned aircraft (200):** Provides a limited set of requirements for recreational activities of RPAS, being also the current area where model aircraft fall into. One of the main aspects is that the user must fly according to guidelines and safety standards of FAA-recognised Community- Based Organization (CBO). The AC 91-57C establishes guidelines with respect to these organisations and their required safety standards.
- **49 USC 44807 Special Authority for certain unmanned aircraft systems (201):** This approach is envisioned for RPAS operations presenting characteristics that are not an option for waiver through Part 107. Here, the applicant conducts a safety risk analysis, which is checked by the Administrator on a case-by-case basis, and measures are established according to the safety analysis results; therefore, it is an ad-hoc approach.
- In the case of **public operations**, one option is to fly under Part 107 if the aircraft and operation comply with their requirements. A second option is through a Certificate of Authorization (COA), which requires an application containing mainly operational information, which is reviewed by the FAA. A third option is provided through 49 USC 40102 (a) (175) or 49 USC 40125, which is intended for public aircraft operations. The latter two procedures are markedly ad-hoc and limited to public operations; thus, they are not included in the Table 3-3 evaluation.
- **Certification of advanced operations:** Another way for RPAS operations is to follow the traditional options to aircraft certification, including alternatives for special air- worthiness certificates and flight permits. In the case of RPAS, as no specific codes are yet available, one of the recommended options is through an experimental airworthiness certificate employing the FAA Order 8130.34D for Airworthiness Certification of Unmanned Aircraft Systems and Optionally Piloted Aircraft (202). However, it should be noted that this document is not a detailed airworthiness code; rather, it employs an approach consisting of an initial evaluation and the calculation of a risk index in order to determine the criteria with which the applicant has to comply, and the level of the safety evaluation considered by the FAA, therefore being again markedly ad-hoc.

(d) JARUS

JARUS is an organisation of experts, with no legal remit, that proposes recommendations for rulemaking, some of which have been adopted by EASA.

With respect to the certified category, within the scope of this research, the CS- LUAS (203) and CS-UAS (179) codes have been analysed. It should be stated that the first was developed following the principles of the legacy Part/CS-23 and therefore contains more detailed requirements; whereas CS-UAS, which is intended for larger RPAS, follows a performance-based approach inspired by the new Part/CS-23 regulations. This explains the difference in level of specificity seen in Table 3-3. It should also be noted that CS-UAS employs the concept of ADS, commented beforehand in section 3.2, and proposes regulations (such as CS-LUAS) or consensus standards to complement the design-independent design criteria found here with more detailed guidelines. However, no direct correspondence of which consensus standard or external document can be used to substantiate the different requirements is provided, in contrast to CS-23 within the manned aviation paradigm, which does provide these connections explicitly. In contrast to the envisioned future framework for CS codes in EASA, here, each CS code contains all requirements, both for the air vehicle as well as for other equipment and the control station.

Regarding the specific category, very recently, JARUS has updated the SORA methodology to version 2.5 (204). This is the main approach, which has been adopted by EASA with some modifications, for operations in this category. It consists of a safety assessment to be conducted attending to aspects of the RPAS and its operation. Depending on the results of the safety assessment, several possible requirements—that can affect, amongst other aspects, the design assurance of the RPAS—are established, thereby constituting an ad-hoc procedure.

(e) NATO

Two detailed certification codes related to RPAS initial airworthiness were found in the document search:

- **NATO Standard AEP-4671 (205):** This document consists of a very thorough and detailed code, with high level of specificity, based on that of the legacy CS-23, with additions in certain points related to RPAS-specific aspects. It is intended primarily for heavyweight fixed-wing RPAS.
- **NATO Standard AEP-83 (206):** This code is focused on lightweight fixed-wing RPAS and is therefore associated with a lower risk of aircraft operations. It has a particular form not seen in other instances, where requirements are laid out in a table with three columns. The first column contains the high-level airworthiness essential requirements, the second one provides detailed arguments that add a

layer of specificity upon the relatively broad guidelines of the first, and the third contains directions with respect to the means of evidence.

(f) Overall discussion and conclusions of stage 1 of the survey

In view of the previous text and of the results of Table 3-3 containing the evaluation of the key characteristics for the aforementioned documents, several aspects related to the set of documents that were analysed and of the overall RPAS international initial airworthiness paradigm can be extracted.

First of all, common concepts and ideas can be found through the different regulatory contexts, which can be expected taking into account the harmonisation efforts. The aforementioned risk-based approach and the concurrent consideration of design and operational aspects to establish the applicable regulations, as mentioned in section 3.2, can be seen in all paradigms. This is in accordance with previous research, which proposed a paradigm where the certification requirements should depend on both dimensions (161). From an RPA design standpoint, this can be seen as an added challenge, as a coupling is added between the operational scenario and the applicable regulations. Even though the design of an aircraft always starts from a set of design missions, not all possible operational scenarios are considered at this stage, which in this case could result in uncertainties regarding the regulatory requirements to integrate in the design stage. Furthermore, these operational aspects do not only cover aspects such as flight airspeeds or cruise altitude, but also whether the operation is above people and the population density or the distance to aerodromes, as it will be seen in the second stage of the survey, where this issue is commented in more detail.

Another common aspect that can be seen in the different paradigms is that, for medium risk operations (such as specific category operations or, in the USA paradigm, operations not yet in the certified paradigm but also outside Part 107 applicability), a safety assessment- based process towards airworthiness assurance is proposed. All of these require a risk analysis to be conducted, and upon the results, a series of mitigating measures with respect to various aspects, including those related to the design assurance of the airframe, are established. This is what has been called an ad-hoc approach in the characteristics for analysis proposed in subsection 3.4.1. As the main high-level approach for the safety assurance of these type of operations is already similar in the different paradigms, a possible further step for regulatory harmonisation could be that the same systematic safety assessment approach (such as the SORA approach by JARUS) could be accepted by the different Authorities. Moving on to aspects related to design, due to the nature of these type of approaches, the possibility of including aspects from these regulations in systematic design procedures that seek to be applicable to a variety of RPAS is hindered. This is due to the precise requirements to be complied with not being established until the end result of the risk assessment, which usually involves a relatively specific knowledge of the aircraft. This, in turn, is not usually available in early design stages where the level of knowledge and definition of the design are low, as commented

in section 8.2. As a further challenge, and in relation to the previous paragraph, the result of the safety assessment is highly dependent on aspects related to the operational scenario (for instance, population density on ground or distance to aerodromes); so, for the same aircraft, and depending on purely operational aspects, requirements related even to the design and components of the aircraft depend on the operational scenario. As an example, following the SORA methodology, an aircraft with a maximum characteristic dimension of over 8m, flying over an unpopulated area with low air risk, is expected to have a Specific Assurance and Integrity Level (SAIL) that does not require specific design criteria for systems and equipment. However, the same aircraft flown over a populated area results in a higher SAIL level, which demands that ADS such as CS-LUAS or EASA SC-Light UAS are employed for the design of components. This further increases the coupling between design aspects and those related to the operational scenario. Taking all of this into account, those approaches following an ad-hoc perspective are particularly challenging to be included in the first stages of design.

It can be seen from the text above that the certified category is the one that still requires more thorough development through most of the regulatory paradigms, with the exception of NATO, which already has well-established detailed certification codes. It is understandable that this category has seen the least development, as the largest volumes of operations are expected within open and specific categories. From a design standpoint, certification codes usually have a high level of specificity, providing the designer with a more straightforward manner to integrate their requirements in design activities, as it will be expounded within section 8.2. Furthermore, the certification of the aircraft allows a certain decoupling from the operational limitations and safety assessments dependent on the particular operational scenario, which are established in open and specific categories, therefore allowing more flexible use of the aircraft, which can be a competitive advantage. On the other hand, the design space is expected to become more limited, as seen in section 8.2, and the designer has to deal with certification activities, demonstrations and costs.

For open category operations or similar paradigms, such as that of FAA Part 107, it is seen that the level of specificity is generally lower than that of the certified category. This is in accordance with the aforementioned risk-based philosophy, where regulatory prescriptions are reduced to avoid hindering operations of low risk (23). In contrast, those documents that are more similar in nature to CS codes, such as the NATO standards, tend to have a higher level of specificity. However, it must be mentioned that there is a particular case in the JARUS codes, the CS-LUAS, which is intended for lighter RPAS, but instead has a higher level of specificity than the CS-UAS, which is intended for larger aircraft, thereby with a higher associated risk. This particularity can be explained since the first code was developed according to the perspective of the legacy Part/CS-23, whereas the second one was developed accounting for the new Part/CS-23 performance-based paradigm, therefore resulting in less prescriptive requirements (23).

Table 3-3. Summary of findings from the first stage of the survey. The table footer contains the meaning of the different symbols employed.

Entity	Regulation	LRD Tier	Legally Blinding?	Topical Focus	Lvl. of Specificity	Streamlined or Ad-Hoc	Availability	Scope	
								Aircraft Type	Operation Category
ICAO	Circular 328 (185)	Tier 1	No	Varied	Low	Streamlined	Public	All	-
	RPAS Manual (207)	Tier 1	No	Varied	Low	Streamlined	Public	All	-
	Chicago Convention Annexes	Tier 1	Yes ^a	Varied	Low-Medium	Streamlined	Payment required	All	Certified
	Part 101 and 102 (189)	Main doc: Tier 1 ACs: Tier 3	No	Operations	Medium	101: Streamlined 102: Ad-hoc	Public	All	101: Open 102: Specific
	Part 149 (190)	Tier 1	No	Organisation approvals	Low	Streamlined	Public	All	Open and specific
EASA	IR 2019/947 (191), DR 2019/945 (192)	Main doc: Tier 1 AMC and GMs: Tier 3	Yes	Operations, design	Medium	Open category: Streamlined Specific category: ad-hoc	Public	All	All
	DR 2024/1108 (208), IR 2024/1110 (194)	Tier 1	Yes	Initial airworthiness certification framework	Medium	Streamlined	Public	All	Specific and certified
	SC-RPAS.SubPartB-01 (197)	Main doc: Tier 2 AMC and GMs: Tier 3	No	Initial airworthiness, design	High	Streamlined	Public	Fixed wing	See footnote b
	SC Light UAS (198)	Tier 2	No	Initial airworthiness, design	Medium	Streamlined ^c	Public	All	Specific
FAA	USC 44809 (209)	Main doc: Tier 1 ACs: Tier 3	Yes	Varied	Low-Medium	Depends on guidelines of organisation	Public	All	-
	Part 107 (210)	Tier 1	Yes	Varied	Medium	Streamlined	Public	All	-

Entity	Regulation	LRD Tier	Legally Blinding?	Topical Focus	Lvl. of Specificity	Streamlined or Ad-Hoc	Availability	Scope	
								Aircraft Type	Operation Category
	USC 44807 (211)	Tier 1	Yes	Assessment of special operations	Low	Ad-hoc	Public	All	-
	Order 8130.34D (202)	Tier 3	No	Experimental certification process	Medium	Ad-hoc	Public	All	-
JARUS	CS-LUAS (203)	Main doc: Tier 2 AMC and GMs: Tier 3	No	Initial airworthiness, design	High	Streamlined	Public	Fixed wing	Certified
	CS-UAS (179)	Main doc: Tier 2 AMC and GMs: Tier 3	No	Initial airworthiness, design	Medium	Streamlined ^d	Public	All	Certified
	SORA (204)	See footnote e	No	Risk assessment of operations	Medium-High	Ad-hoc	Public	All	Specific
NATO	AEP-4671 (205)	Main doc: Tier 2 AMC and GMs: Tier 3	No ^f	Initial airworthiness, design	High	Streamlined	Public	Fixed wing	Certified
	AEP-83 (206)	Tier 2 and 3	No ^f	Initial airworthiness, design	Medium-High	Streamlined	Public	Fixed wing (mainly)	Certified

a: Albeit the Chicago Convention Annexes satisfy the definition of “standard” according to ICAO, it is permitted in special cases that Contracting States do not comply with some aspects, as long as they notify differences. **b:** The SC was developed attending to the previous paradigm of EASA as established by the Policy E.Y013-01, and it is applicable for RPAS for which the kinetic energy assessment according to this Policy results in an initial certification basis according to CS-VLA, so it can be considered to be associated to the certified category. **c:** Albeit the content is streamlined, the regulation is applicable to RPAS with a resulting SAIL of III or more within the specific category, which does depend on a prior safety assessment. **d:** Due to heavy emphasis on performance-based requirements, and the need to complete certain requirements with ADS, establishing a certification basis might tend towards a slightly ad-hoc approach. **e:** SORA is a particular case as it does not follow the typical structure or spirit of certification regulations. **f:** Not legally binding in the civil field; however, it is legally binding in NATO Signatory States that have adopted it.

From a designer's perspective, there can be both positive and negative aspects of having either less prescriptive requirements with lower specificity or more prescriptive ones with a higher specificity level. On the one hand, following the principles of the performance-based and risk proportionality paradigms, it could be argued that qualitative regulatory criteria with low level of specificity result in more flexibility for the designer and a wider array of possibilities on deciding how to implement and substantiate the requirements. This could be considered in line with the aforementioned criteria of not placing excessive regulatory pressure on the applicants in areas where it is not as critical. Furthermore, there could potentially be more flexibility on the design solutions, as the criteria can be complied with through different means. On the other hand, requirements with a high level of specificity could be integrated in a more straightforward way within design methods. Furthermore, and since these high specificity requirements usually give quantitative criteria, this could eliminate potential uncertainties on the certification process regarding whether an undetailed requirement will be considered by the Authority as having been met or not, which could be very dependent on the specific substantiation approach selected by the applicant. Therefore, it could be said that requirements with higher specificity could potentially be more demanding on the design, but they also give larger certifiability assurance, since checking whether they are complied with or not is more straightforward. There are further aspects to be considered regarding the way in which requirements with different levels of specificity influence the restrictions and evolution of the design space, which shall be discussed in further detail within section 8.2.

At this point, it should be noted that the possible negative aspects of having a lower level of specificity, which are mainly related to a lower assurance on the certifiability of the design, could be offset by the use of AMC and GM that have a higher level of specificity. The result of this would be that the designer could have the option to follow more prescriptive requirements with a higher specificity level if desired, but this would not be a mandatory process, thereby also leveraging the advantages of performance-based regulations of allowing for a larger feasible design space and not constraining the design process and the ways of demonstrating airworthiness compliance. However, for this to be in effect, a clear correspondence is needed between the performance-based requirements and the applicable lower-Tier but more specific documents. This is not currently the case in the field of RPAS within the few certified category documents available, Particularly in CS-UAS, where (albeit CS-LUAS and CS-LURS are recognised as possible ADS to the aforementioned regulation) no detailed provisions or other alternatives are provided, which makes the selection of ADS a relatively ad-hoc process. Also related to this issue, it should be noted that no Tier 4 documents have been found in the survey within the scope of the review. Several entities have developed standards for RPAS, such as the American Society for Testing and Materials (ASTM) (212; 213; 214), ISO (215; 216), the European Organisation for Civil Aviation Equipment (EUROCAE) or the Flight Safety Foundation Basic Aviation Risk (BAR) standards. However, these documents could not be accessed without payment, therefore leaving them outside the scope of this work. Future

documents within the public domain dealing with specific aspects of RPAS design that could be employed as ADS could constitute a paramount advantage to the field.

In contrast with the relatively vague ADS selection process in RPAS, CS-23 does offer an unambiguous correspondence between each requirement and the applicable consensus standards or past regulations that can be used if the designer seeks a higher level of specificity. Should future editions of the aforementioned RPAS documents, or the future EASA certified category paradigm, be more aligned with the organisation of the new CS-23, along with the aforementioned development and proposal of standards in the public domain, it can be argued that this would be advantageous for the aircraft designer, allowing for greater flexibility in certification basis selection while also providing detailed guidelines to which they can adhere. It should be noted that this standpoint of having high-level flexible requirements with low specificity complemented by lower-level alternatives to show compliance with the first ones can be considered to have been explored, within the same document, in the AEP-83 (206), as seen in the text above.

3.5.2. Stage 2: Design and Operational Applicability of Selected Documents

In this subsection, further aspects of the previously studied documents shall be analysed, focusing on additional features which are also of particular relevance to the aircraft designer. Specifically, the design and operational applicability ranges of the documents shall be considered. This is essential for the aircraft designer, as it is crucial to know, from the earliest possible point within the design continuum, with which airworthiness requirements the design must comply. These specifications vary to a great degree among distinct regulations, so the documents which are pertinent to the aircraft concept that is being designed must be selected so as to select the proper certification basis.

Firstly, the group of documents analysed in the previous stage will be trimmed down, so as to keep those which are more useful towards their integration in design approaches. Following the discussion at the end of the previous subsection, these would be those that present streamlined requirements, and those that focus on the initial airworthiness of the airframe. It was mentioned beforehand that documents with a low specificity level could also present more difficulties for their incorporation in design methods. However, as it will be developed in detail within chapter 8, qualitative requirements can also be used in various ways by the designer, even if they do not provide a high certifiability assurance or a clear-cut restriction, thus they will be kept for this second stage of the review.

The documents that have been omitted when compared to the previous stage are as follows:

- 1) Those that followed ad- hoc approaches, due to the limitations they offer for integration in design activities as mentioned beforehand.
- 2) Those that are not focused in the airframe design or operational constraints, such as ICAO Part 149 or EU DR 2024/1108 and IR 2024/1110.

- 3) Documents whose content is not yet definitive or could not be accessed, namely, the Chicago Convention Annex amendments.

Two main dimensions have been evaluated with respect to document applicability: design limitations, which are related to the RPA airframe characteristics; and operational considerations. These two dimensions link with the coupling of design and operational characteristics in the field of RPAS that was mentioned previously. It should be noted that certain operational aspects, such as operational constraints or design mission objective criteria, can have a critical influence in design and are therefore considered in design methodologies. In fact, in some cases, design requirements such as completing a certain mission over complicated terrain can constitute critical restrictions to the RPAS design, as seen in (24; 217). The results from this analysis can be seen in Table 3-4.

One of the foremost conclusions that can be extracted from this table is that, even having excluded from the analysis particular cases of the regulations such as waivers and special procedures, there are many particularities to consider even for the operational restrictions, as can be seen in the table footnotes. Therefore, it can be concluded that a specialised level of knowledge in the regulations is required so as to fully cover all considerations. However, it is expected that a designer that wishes to develop an aircraft with a relatively broad operational spectrum would opt for the main processes that are less ad-hoc, which are the ones that have been included here.

With respect to the applicability of the different regulations, and firstly attending to design aspects, it can be seen that, with the current paradigm, the spectrum of MTOM values is broadly covered but there are some overlaps between regulations, particularly within the certified category. While the criteria for separating CS-LUAS and CS-UAS has been mostly based in the difference between CS-VLA and CS-23, the NATO standards establish a different threshold. With respect to operational considerations, except perhaps for the max speed, most of the other aspects are related to the specific operational scenario rather than to performance characteristics of the airframe; thereby, they are of more use to the operator than to the aircraft designer. Overall, it can be seen that, even regarding the applicability of regulations, the scenario is notably heterogeneous, in spite of the advances in recent times towards a more homogeneous framework.

Table 3-4. Summary of findings from the second stage of the survey. The table footer contains the meaning of the different symbols employed.

Entity	Regulation	Design Applicability				Operational Restrictions			
		Mass (MTOM)	Aircraft Type	Operation Category	Impact Energy	Max. Speed	Max. Height	Distance to Aerodromes	Proximity to People
ICAO	Part 101 (189)	<25 kg ^a	All	Open	-	-	<120 m AGL	>4 km	>30 m
EASA	Subcategory A1 (191)	C0: <0.25 kg C1: <0.9 kg ^b	C0, C1: electric powered	Open	C1: <80 J terminal velocity	C0, C1: <19 m/s	<120 m AGL ^c	See note d	No overflight of assemblies
	Subcategory A2 (191)	C2: <4 kg	Electric powered	Open	-	-	<120 m AGL ^c	See note d	>30 m
	Subcategory A3 (191)	C2: <4 kg C3, C4: <25 kg ^b	All	Open	-	-	<120 m AGL ^c	See note d	>150 m
	SC-RPAS. SubPartB-01 (197)	See note e	Fixed wing	See note f	Unpremeditated descent: <0.003 MJ, LOC: <0.02 MJ	-	-	-	-
	SC Light UAS (198)	See note g	All	Specific	See note g	See note g	See note g	See note g	See note g
FAA	Part 107 (210)	<25 kg	All	-	See note h	<44.8 m/s	<122 m AGL ^c	See note i	Generally no overflying ^e
JARUS	CS-LUAS (203)	<750 kg	Fixed wing	Certified	-	-	-	-	-
	CS-UAS (179)	Non-VTOL: <8618 kg VTOL: <3175 kg	All	Certified	-	-	-	-	-
NATO	AEP-4671 (205)	Mainly 150–20,000 kg	Fixed wing	Certified	-	-	-	-	-
	AEP-83 (206)	<150 kg	Fixed wing	Certified	>66 J ^j	-	-	-	-

AGL: Above Ground Level, **LOC:** Loss of Control, **MJ:** Mega Joules. **a:** Additional requirements must be met for RPA between 15 kg and 25 kg. **b:** Some privately built and legacy RPA can also operate in these subcategories. **c:** Can be exceeded to overfly an obstacle. **d:** No detailed provisions are given in the Regulations or their AMC and GM, but it is expected that most aerodromes are considered as “restricted geo-zones” for the operation of RPAS, therefore restricting operations in their vicinity save for prior authorisations. **e:** Applicability depends on kinetic energy, combining mass and velocity. **f:** As per footnote b in Table 3-3. **g:** Characteristics resulting from the safety assessment conducted prior to employing the Special Condition. **h:** Different types of operation depending on impact energy and proximity to people are established. **i:** No specific distance given, but Air Traffic Control (ATC) permission is required to operate within lateral boundaries of the surface area of Class E airspace designated for airports. **j:** An Appendix of the regulation includes a reduced and higher-level set of requirements for impact energy below 66 J.

A remarkable aspect, which is related both to airworthiness and design considerations, is that operational restrictions only appear within regulations of the open category, whereas in the certified category no such limitations are present. This is tightly related to the methods used by the Authorities for safety assurance in each of the categories. In the case of open category, as it is not intended that combinations of aircraft and operational scenarios with overall low associated risk have to go through the lengthy and expensive process of certification, which could hinder the development and usage of RPAS, and would not be according to the principle of proportionality as mentioned in section 3.2, the safety assurance is achieved instead through operational limitations that allow control of the risk—that is, there are few restrictions on the design but relevant limitations in the operational scenario. On the other hand, for the certified category, which is usually related to aircraft and operational scenarios with a higher combined risk, the most emphasis is placed on the design, through compliance with detailed certification codes, in order to reach the desired safety assurance level—that is, if a large RPAS has to be flown over a populated area, as the concept of operation itself includes a high level of risk, then the safety assurance is achieved through a certification process for the RPAS, which allows to control the overall risk to an acceptable level and in turn provides larger operational flexibility. This explains why the certified category documents included in Table 3-4 contain no operational limitations, as the risk to be managed through the safety assurance has been absorbed through certification.

Finally, an aspect which—albeit not compiled by Table 3-4—has been observed within this second stage of the survey, is that the level of specificity at the requirement level when comparing similar topics on different regulations can vary greatly, even for codes sharing a significant MTOM interval. As mentioned in subsection 3.4.1, the level of specificity can be evaluated both at overall regulation level and at specific requirements level. The latter is essential when extracting particular airworthiness-driven restrictions for design, as it will be covered by one of the steps of the DECEX procedure to be expounded in section 8.4. For instance, regarding the topic of operational airspeed definitions, such as the Maximum Operating Limit Speed (V_{MO}) or the Never Exceed Speed (V_{NE}), NATO AEP-4671 provides detailed definitions and their requirements and relationships between them, which would result in a high specificity level at requirement level. However, CS-UAS, with which the aforementioned standard shares a significant applicability overlap in MTOM range, only contains broad guidelines, stating that the applicant must determine relevant structural airspeeds, but not giving specific calculations or the explicit relationships between these speeds, resulting in a low level of specificity. This could be expected since at regulation level the level of specificity of the CS-UAS is lower than that of AEP-4671.

Aside from the differences in level of specificity of specific requirements, discrepancies can also be observed in their content and numerical constraints for those cases when the specificity is high. For example, among the certified category codes, these disagreements can be observed for different topics, such as stall, climb, manoeuvring and gust specific requirements. An exhaustive review on the differences between each singular

requirement of the regulations would be outside the scope of this survey. In any case, the certification requirements to be integrated in a design methodology would depend on its design stage and scope, which constitutes a challenging aspect towards development of airworthiness-based design methods, as it will be discussed within chapter 8. The effect of discrepancies in level of specificity and also between numerical constraints at the requirement level shall be discussed in section 8.4, where the DECEX procedure that is developed there seeks to solve some of the issues that could arise due to these matters. This will be further illustrated in the two cases of design criteria extraction from regulations that will be developed there. In particular, these will cover the aforementioned topics of stall, climb, manoeuvring, and gust, as a way to showcase the way in which the use of DECEX can also serve to conduct particular design-airworthiness integration analyses at the requirement level.

3.6. Summary and conclusions

The research presented here has surveyed the current international landscape of RPAS initial airworthiness regulations from the perspectives of airworthiness and of the integration of these requirements in design methodologies and processes. The most noteworthy contributions of the research conducted in this chapter would be the following:

- 1) The definition of the criteria proposed in subsection 3.4.1 to scrutinise the regulations, considering both airworthiness and design–integration aspects.
- 2) The up-to-date survey, accounting for both design and airworthiness characteristics, which has been conducted on the international paradigm of RPAS initial airworthiness, having analysed some documents that are particularly recent and, thus, were not considered in previous works.

With respect to the results of the survey, several aspects have been highlighted along the previous discussion, both related to airworthiness and to the impact of the characteristics of regulations in design aspects. One of the main findings is that there is a significant heterogeneity between regulations for similar aircraft and operational categories across different international entities, as seen in section 3.5, which can lead to difficulties towards uniform compliance and towards designing RPAS for global market access. Furthermore, RPA regulations generally present a lower level of specificity compared to traditional manned ones. On the one hand, this can be regarded as negative, resulting in a lower certifiability assurance and streamlining when designing and certifying RPA. On the other hand, it can be regarded that the low level of specificity provides benefits in avoiding highly prescriptive requirements and procedures that could hinder expansion and innovation within the field of RPAS. This ties in with the high-level philosophies of risk-based and performance-based approach mentioned in section 3.2. In fact, regulators themselves have acknowledged that there is significant activity in the field of SMEs

particularly in small RPAS applications, which is one of the reasons for their interest in keeping the regulatory barriers low for aircraft and operations posing a comparatively reduced risk.

A possible balanced approach proposed here that could satisfy both viewpoints might be achieved through the concept of ADS proposed by JARUS: the main, legally applicable regulations would be performance-based and with lower specificity but having a clear and unambiguous correspondence of each requirement with publicly available consensus standards or AMC and GM that can raise the level of specificity and, being approved by the Authority, provide certifiability assurance following more streamlined processes that are easier for the designer. In order to accomplish this, the following two points would be required to be covered:

- 1) More ADS would be required to be developed so as to provide higher specificity alternatives for the designer. Taking into account the wide design variety of RPAS, as showcased in Figure 1-3 at the beginning of the thesis, it is likely that a relatively wide range of ADS would be needed to cover design particularities of the different layouts.
- 2) An unambiguous correspondence would be needed between main regulation requirements (such as those of CS-UAS) with the applicable ADS, in a similar way to the new Part/CS-23 in the field of manned aviation. This would allow the designer to know with certainty which procedures are accepted to demonstrate compliance with each requirement.

In spite of the recent surge in development of the RPAS regulatory framework, this field still presents several avenues which are yet to be covered, such as the EASA certified category. The survey has sought to discuss not only the current regulations, but also the expected future developments, as established by the Aviation Authorities in their different rulemaking documents. In view of the fact that there are still forthcoming developments, it is possible that the aforementioned two points which could aid in tackling the specificity issues will be covered in the near future. However, this is ultimately in the hands of the regulators, and for the time being, the designer is still faced with the previously mentioned challenges.

Finally, there is an added obstacle affecting airworthiness-based design methodologies, that is not posed by characteristics of the regulations themselves, such as the ones mentioned before, but rather associated to a key aspect of the regulatory framework overall, which is its high dynamism. The survey presented in this chapter has analysed currently applicable standards and recommended practices, but before these, there were others previously in place, as seen in the timeline of Figure 3-1. Not only have specific regulations changed with time, but also the main guiding rulemaking philosophies, whose effects are manifested downstream in the standards which are produced following them. For instance, albeit the EASA Policy Statement E.Y013-01 issued on 2009 considered the

option of regulating by safety objectives, the main path towards certification was through selecting a reference code adequate for the RPA and adapting its certification basis. At that point, the performance-based approach, which is widespread nowadays in the domain of RPAS, was not yet established. Thus, with the changes that have occurred in the short and medium term, design methodologies developed with previous airworthiness requirements in mind would generally not be applicable in today's framework to develop certifiable aircraft. In the same way, and since the paradigm is still in construction, design methodologies implementing current requirements might cease to be valid in some years. Thereby, this constitutes a challenge not towards the development of airworthiness-based approaches themselves, but rather to their continued validity and applicability to design certifiable aircraft. In contrast, this is rarely a hurdle within the realm of manned aircraft, as the regulations there are much more mature and stable.

Even if the current RPAS regulatory framework is still in development process, and in spite of the aforementioned ways in which the current scenario challenges the designer, one of the foremost objectives of the novel design methods to be developed in part III of this thesis is the integration of airworthiness requirements in RPA design approaches, which as seen in section 2.2, is still a largely unexplored avenue in this domain. The survey and discussion developed here shall serve as the foundation of the work to be developed in chapter 8, where the difficulties that the current framework entails towards the development of airworthiness-based design methods shall be tackled.

4. REVIEW OF FIXED-WING AIRCRAFT COMPUTERISED DESIGN ENVIRONMENTS

This chapter covers the evaluation of the current state of manned aeroplane and of fixed-wing RPA computerised design environments, which is one of the three key areas for assessment as established in OBJ.2.2 within section 1.4, and as supported by the findings of the overall literature review of RPA design as discussed in section 2.3. As seen beforehand, these programs provide numerous advantages to the designers, allowing them to tackle complex and multi-stage design problems while leveraging the advantages of computer-aided analysis and synthesis. It was already seen in section 1.3 that RPAS present numerous novel design challenges, mainly due to their dissimilarities when compared to traditional manned aircraft. Thereby, in the same way that manned aircraft design packages have aided designers in overcoming relevant hurdles within that field, computerised design environments for RPA could harbour the potential to tackle some of the current open challenges in RPA design.

In spite of this, as anticipated through the findings of the overview of the state-of-the-art of section 2.2, there appears to still be room for improvement within the area of computerised design environments for RPA. Currently, very few design packages have been developed specifically for this type of aircraft accounting for their particularities. Moreover, albeit various of the available packages cover some tasks and models related to conceptual design, there is a general lack of overall initial sizing approaches integrated within them, with rapid systematic methods for sizing of the tail surfaces and fuselage being mostly missing. These issues support the purpose of conducting a more thorough review on the current status of not only RPA design environments, but also those of the more mature area of manned aircraft. This is expected to allow to see which are the current capabilities of these environments and what are the challenges that they are facing nowadays, so as to evaluate the current scenario with respect to their potential application in RPA design endeavours.

4.1. Chapter introduction and overview

As introduced in subsection 2.1.4, aircraft computerised design environments are software suites whose main objective is to aid the designer in conducting analysis and synthesis tasks towards the solution of aeroplane design problems (59; 70; 94). They accomplish this by integrating within a common framework several tools and models related to the various disciplines of the aircraft design process (17), with their combined use serving to produce results which allow to perform the initial sizing of an air vehicle concept, or to update and refine its definition; thereby contributing to the advancement of the aircraft design process. In subsection 2.1.4, a preamble to this topic was expounded, with particular emphasis on the definition employed through this thesis of aircraft computerised design environments, as well as their distinction with respect to other types

of computer programs and frameworks related to aircraft design and analysis. Various examples of aircraft design packages were also provided therein.

The benefits derived from the use of these programs were outlined beforehand in subsection 2.1.4 and have been well documented within previous works in the state-of-the-art. These include, but are not limited to: allowing the designer to manage the different activities and models involved in the design continuum (41); enhancing the synergies among disciplinary analyses (17); reducing the time required to prepare analysis workflows and simulations, as well as that needed to perform the necessary calculations (70); augmenting the quality and accuracy of the aircraft concepts (70); enabling to perform complex technology trade-offs and sensitivity analyses (51); improving the design exploration process in search of promising aircraft concepts (41); increasing the volume of aircraft concepts which can be evaluated and compared at a given time (70); aiding in the validation of analysis models (51); and contributing to a shorter lead time to further design stages (70). Various other advantages of these environments shall be explored through the present chapter.

The last two decades have seen a remarkable interest in the development and improvement of numerous aeroplane computerised design environments, with research in this field being increasingly active (91). Many of these design packages are still being maintained and updated by different universities, research institutes, aeronautical companies and other organizations. It is understood that the appeal of this research area is motivated by the advantages that these computer programs provide to the designer, as it has been commented beforehand. However, it can be argued that the recent surge in their interest has also been driven by recent challenges concerning the broad field of aeroplane design, for which these computer programs can potentially constitute relevant assets to address these hurdles. Since the main objective of these packages is to aid the engineer in current aircraft design tasks, it can be expected that their functionalities and advancements are tightly interlinked with the main contemporary trends and concerns in the overall field of aircraft design. A brief overview of some of these issues is expounded below, covering both the fields of manned and unmanned aviation.

It has been pointed out in previous research that aircraft are becoming increasingly complex with each generation (41; 218), which is a trend also seen in the area of RPAS (17). This affects the intricacy of the design process that is needed to arrive at more involved aeroplane concepts, so updated methods and tools are required to better aid the designer in managing this growing sophistication. The steady increase in available computational power and software implementation solutions (100) can be leveraged to develop advanced computer environments seeking to support the designer in better tackling this demand, contributing to address more complex aircraft design methods and concepts through the use of these software. Thereby, it can be argued that the increase in aircraft design intricacy is also driving an growth in the complexity of computerised environments themselves (100).

In tight relationship with the previous point, one of the main challenges being faced by the aircraft design community in recent times is the development of novel analysis and synthesis procedures which can address the design of unconventional configurations (59; 219). These include layouts such as Blended Wing Body (BWB), joined wing, box wing, tandem wing, and tri-surface configurations, among others. The main driver motivating the study of these atypical layouts are the demanding environmental and efficiency targets in the aviation industry (220), as pointed out by previous authors (58; 91). It has been remarked that it will be difficult for traditional aeroplane layouts to meet these targets, thus the aforementioned revolutionary configurations are increasingly being considered as potential candidates which might achieve the aforementioned demanding goals (12; 58; 91). The range of potential aircraft concepts has become more diverse and complex in recent times, constituting a remarkable area of research (59). These unconventional configurations add additional layers of intricacy to the design process, increasing the need of modern tools to support the designer's tasks, thus also augmenting the demand for updated computerised design environments which can conduct design tasks on these novel aircraft concepts.

Furthermore, there are other contemporary trends in the field of aircraft design which also have an effect in the organisation of the design process. These include a higher degree of specialisation in engineering teams (70; 74; 97; 155), a growing emphasis on collaboration and concurrent engineering (41; 74; 97; 155), as well as an increasing decentralisation of design teams and computational resources (70; 74; 155; 221; 222). As commented beforehand in subsection 2.1.4, aeroplane computerised design environments are not only software implementations of design methodologies, but also comprehensive tools aiding the engineer in tackling the diverse design tasks. Thereby, design packages have also been proposed as assets that can aid in navigating these recent trends, which demand a higher effort in laying out distributed computational frameworks and enhanced workflow management capabilities (92; 155; 222).

Aside from the aforementioned issues, there are other relevant trends being currently investigated in the area of aircraft design environments, some of which are also related to the ones mentioned above. For instance, recent advancements in computational capabilities have increasingly enabled these design packages to integrate a greater number of complex calculations pertaining to higher fidelity approaches, such as Finite-Element Analyses (FEA) and Computational Fluid Dynamics (CFD), the results of which are fed back to the design loop (55; 85). This is leading to these design packages to cover more extensively the different phases of the design process, not only limited to the early stages. In spite of this, recent computerised design environments also highlight the relevance of low fidelity methods in their workflows, emphasising the advantages in computational resources derived from adequately leveraging rapid analysis methods (59; 70). Furthermore, these environments are becoming increasingly holistic, covering more areas which intertwine in aeroplane design through more modules that cover different

design disciplines. They have also experienced recent enhancements in their capabilities of analysing diverse missions and a wider array of performance metrics (100).

As it can be seen, the area of computerised design environments is notably dynamic and shows particular promise, since not only do these programs provide remarkable advantages in solving traditional aircraft design problems, but they may also constitute a fundamental asset in tackling some of the novel challenges in the broad field of aircraft design. In particular, they have also shown promising prospects regarding their use in RPAS design, which is the central topic of this thesis. In fact, as outlined in the broad literature review of the field of RPAS design of section 2.2, it was seen that some design environments for RPAS have already been developed, albeit this area is not as mature as that of manned aeroplanes.

The process of updating existing design packages, or even developing new ones, to address the aforementioned objectives and challenges constitutes a significant line of work in itself. It should be noted that relevant hurdles have been detected in current design environments which can difficult their capability to tackle the issues commented beforehand. Two relevant types of limitations have been brought forward by previous authors in this regard:

- 1) Limitations in the applicability of current methodologies to other aircraft concepts (17; 91). This links to the potential lack of validity of current packages for the design of unconventional configurations and RPAS, thus it is also related to one of the main challenges for RPA design as commented in section 1.3.
- 2) Limitations in the flexibility and scalability of certain tools (17; 91). This can impact the possibilities of updating them to cover the aforementioned challenges, among other aspects. It can be seen that this links to a certain extent with aspects that are more related to software architecture and engineering.

In view of the above, and considering the relevance of computerised environments within the overall area of aircraft design, a thorough assessment of the current state of this field could constitute a remarkable asset. This would allow to uncover the main lines of work in this area, and the present scenario regarding the capabilities of present computerised design environments and how they are tackling the current trends and challenges mentioned beforehand. In the context of this thesis, it is of particular interest to evaluate to what extent current design environments address the particular challenges of RPA design. For this, it is necessary to assess how the current features and capabilities of these software align with the main characteristics of RPA and their foremost design challenges. These perspectives set up the context for the review which shall be conducted within this chapter.

Before moving forward, it should be highlighted that most of the aforementioned trends and challenges link with the two main areas of interest in the field of aircraft

computerised environments as seen in subsection 2.1.4, which were described in detail there and are listed here again:

- 1) The first is related to the **implemented design methodologies themselves**, as well as their capabilities. This links with the aforementioned issues of applicability of traditional design methods to unconventional configurations and RPA, and also connects with the first type of limitation in computerised design environments mentioned above.
- 2) The second is related to **software architecture and computational aspects**. For instance, the above-mentioned second type of limitation related to the scalability of certain design packages would be related to a considerable extent with this area.

The above-mentioned two areas shall be taken into account along this chapter, and the topics which will be object to review here shall cover them both. Even though the main focus of the thesis is on design methodologies themselves, and thus more aligned with the first area, it will be seen through this chapter that computational aspects also have a significant impact on the implementation and deployment of the design methods themselves, thus also affecting their practical capabilities. Thereby, advancements in the second area can enable improvements on the design packages which can, at the same time, allow to tackle hurdles related to the first one. However, it has only been recently that this second dimension is being considered and covered more extensively within the state-of-the-art. In spite of aspects related to the design and analysis problem solving structure having been pinpointed as having a similar importance to the accuracy of the analyses themselves (51), software architecture, workflow, and interoperability considerations have been relatively neglected up until the recent times (68). This is why recently there is a larger emphasis on the second area, with current design packages paying more attention to topics such as software architecture, data structures, problem workflow, tool interoperability, and method implementation, among other dimensions related to computational aspects (35; 41; 55; 91; 92). These considerations support the emphasis on characteristics related to both areas within the review to be carried out in this chapter.

4.1.1. Chapter objectives and structure

Within the context of the thesis, the review conducted in this chapter seeks to evaluate the status of computerised design environments regarding their possibility of tackling the current design challenges of RPA, and how they could contribute to solve some of the main hurdles in this area. It is sought to assess whether the capabilities of current tools could be aligned with the accomplishment of the main objective of the thesis, which is the development of methodologies for the initial stages of fixed-wing RPA design. That is, it is intended to evaluate whether conceptual design methodologies for these aircraft are already available and to what extent within current RPA design environments. In the case that gaps are detected in the capabilities of these tools towards achieving the

aforementioned purpose, a set of objectives and key features shall be proposed towards the development of new RPA computerised design environments which can cover the conceptual design tasks of these aircraft.

However, the review shall not only focus on computerised design environments specific of RPA, of which there are currently few available, as seen in section 2.2. The interest of design packages within the overall field of aircraft design merits a thorough review including the much more mature realm of manned aeroplane design. This does not only allow to broaden the scope of the study, but also provides a more cohesive picture of the overall field of computerised design environments, as in many cases the hurdles of both areas intersect, and ways in which the relevant challenges have been tackled for one of these aircraft types could be compared with those used for the other type. Furthermore, it shall also allow to contrast the current status and capabilities of both of the design packages developed for both types of aircraft.

Taking the above into account, and within the context of OBJ.2.2, its goals can be further divided in three main objectives that will be covered along this chapter:

- 1) **Analysis of the current trends and challenges in computerised design environments:** this objective is related to scrutinising the current literature on the subject to identify the main current trends in this area. Some of these are a result of the intended use of these environments to tackle key hurdles in the overall field of aircraft design (such as the design of unconventional configurations or RPA), whereas others are more intrinsically related to design packages themselves and the purposes of increasing their capabilities, effectiveness, and efficiency (such as enabling a higher degree of interoperability among the different modules of these tools). The approaches which are being employed nowadays in relation to each of the trends shall also be identified.
- 2) **Evaluation of key features of existing computerised design environments:** this will provide an updated picture on the capabilities of design suites which have already been developed. In particular, it is intended to see the extent to which the current capacities of these packages allow to cover the challenges analysed above, to detect potential gaps and future lines of development. To this end, firstly, a set of features shall be defined in relation to the trends and challenges detected beforehand. Then, it will be seen how many design environments among the ones studied in this chapter present the aforementioned characteristics. The analysed features shall also cover aspects related to the types of aircraft which the tools cover within their scope, the disciplinary modules that they integrate, and computational aspects which aid to enhance these software tools, among others.

- 3) **Assessment of the current state of design environments in relation to RPA design, and identification of key features towards future RPA design packages:** from the previous points, the extent to which current environments cover the objectives and challenges of RPA design shall be assessed. This will allow to see to what extent current tools have covered some of the overall objectives of the thesis, or whether future work is required in this area. In case that the latter is true, key features required for the development of conceptual design environments that can cover the initial sizing stages of RPA design shall be proposed.

It is noted that the first two points are mainly related to thesis contributions of the review type (RCT.1), whereas the third one is associated with the contribution type of assessments and original insights (RCT.2), as commented in the thesis introduction. The outputs from these insights shall link with key criteria employed in the development of the novel design methodologies for RPA initial sizing in part III of the thesis.

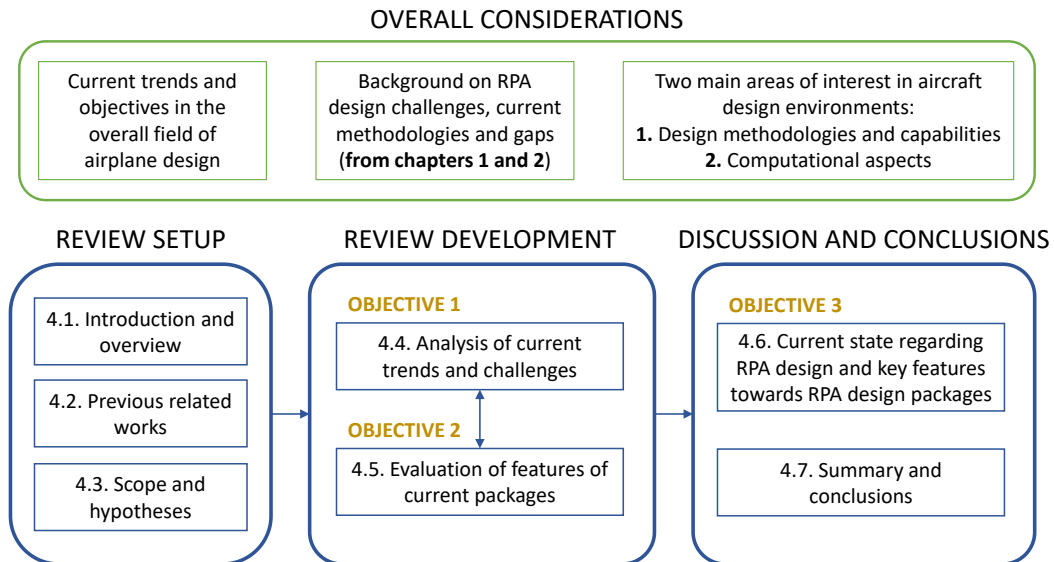


Figure 4-1. Schema of the contents of the chapter, showcasing their relationships with the three main objectives and presented along with overall considerations for the review and discussion.

The structure of the remainder of this chapter shall follow the schema described here. In section 4.2, some previous related works are briefly commented, which include previous surveys of computerised design environments. Then, section 4.3 establishes the main scope and hypotheses governing the review. The review proper shall start with the analysis of current trends and challenges in this field, which is developed in section 4.4, and serves to cover the first of the objectives of the chapter. Then, section 4.5 conducts the assessment of key features of computerised design environments. The characteristics themselves shall be defined attending to the trends and hurdles analysed beforehand, and the degree of implementation of these features in the current framework of design packages shall be assessed, covering the second objective. The review results provide the

main material for the discussion conducted in section 4.6, where the current state of computerised environments for RPA is evaluated and lines of future work are proposed. Finally, section 4.7 provides the close of this chapter. The schema of the different parts of the chapter, and their relationship with overall considerations and the three objectives stated beforehand, are provided in Figure 4-1.

4.2. Previous related review works

Before moving forward, it is noted that in broad terms two different kinds of research works can be found in the open literature related to aircraft computerised environments:

- 1) Those which document the development, capabilities and practical application of a particular design environment, which is usually developed by the authors themselves.
- 2) Those that evaluate the overall field of computerised design environments, providing a review of existing design packages, comparing the capabilities of some of them, and commenting the overall trends of this area.

The work developed in this chapter, being a review of existing design environments, would fit within the second of these types. However, in order to conduct the review presented here in sections 4.4 and 4.5, several research works of the first kind will have to be analysed. These shall be cited and commented through the survey itself. In contrast, the purpose of this section is to cover some of the previous works in the second field, which are those more directly comparable to the investigation developed in this chapter. This will allow to outline the main differences of the survey conducted in this thesis when compared to previous ones. Furthermore, some other related research will be mentioned.

Firstly, it should be noted that some of the works which have carried out the development of previous design environments have also included an analysis on previous design packages, with the objective to identify research gaps and select the areas which their particular computerised environment are going to cover. Some of the previous works which have developed design packages themselves but also include a comparatively ample overview of previous environments are those of (41; 59; 76; 91). Their emphasis is mainly on the types of layouts which previous design packages can analyse, as well as their overall analysis capabilities. In both cases, they employ the findings from their state-of-the-art analysis to guide the developments to be implemented within their own packages.

Other works do not seek to develop their own design packages, rather, they conduct surveys which provide a contemporary picture of this area within the open literature, this being the main contribution of their investigations. These works usually analyse a larger number of previous design environments and develop a more in-depth assessment of them. Often, the purpose is not to go over each package commenting on their specific

characteristics, rather to evaluate and discuss the combined landscape formed by the group of design environments that area being analysed. This shall also be the approach of the work conducted within this chapter, which is aligned with its purposes, as the objective here is to address trends and features of the whole paradigm. Regarding previous reviews in the state-of-the-art, firstly, the research of (68; 100) analyses in its first part various design environments, whereas the second delves into the area of integration frameworks, which as it will be seen later on is among the most noteworthy current trends within this field. The up-to-date investigation of (63) covers a wide array of design environments, and the focus here is to analyse the overall trends regarding optimisation capabilities as well as the methods available for different disciplines, such as aerodynamics, structural analysis, mission analysis, or costs. For each of these areas, analysis procedures pertaining to various levels of fidelity are examined. Finally, the work of (223) follows a different approach, as it performs an in-depth assessment and comparison of two specific design packages, comparing their performance when tackling the same design problem.

As expounded in subsection 2.1.4, the definition adopted in this thesis of computerised design environments would exclude computer programs which are only focused on analysis and do not integrate a design loop that modifies the geometry of the aircraft according to the results from the analysis. Furthermore, standalone MDO frameworks that are not integrated within programs covering various other tasks of the design workflow would also fall outside the scope of the proposed definition. In spite of the above, two more works are mentioned here which, albeit they do not conduct reviews of design packages themselves according to the definition adopted here, they constitute relevant surveys related to this topical area. An exhaustive review on the applications and capabilities of MDO in air vehicle design can be found in (224); and for the particular case of RPA design, a previous study developed a comprehensive review of currently available open-source disciplinary analysis software which could aid in the design and analysis process (225).

The review conducted in this chapter is aligned with the overall objectives of the thesis, which gives it a distinct focus in comparison to previous works, particularly considering the emphasis on RPA design aspects here. In contrast with previous surveys, the one conducted in this chapter seeks to analyse the interplay between the current trends of the field of computerised environments with the capabilities currently implemented by these packages, making a explicit correspondence between the features to be evaluated in the second part of the survey with the challenges analysed in the first part. Furthermore, the emphasis on aspects related to RPA design, the evaluation of the capabilities of current packages related to this field, as well as the proposal of future lines of work to enhance their applicability to the synthesis of these aircraft, constitute novel contributions of this work in comparison to previous design package surveys.

Finally, it should also be noted that some time has passed since most of the previous surveys mentioned along this section were conducted, so the review developed here would also constitute an updated perspective of this field, taking into account its recent developments.

4.3. Scope and hypotheses of the computerised design environment review

The first fundamental step in establishing the scope of this survey is to set up a definition of what constitutes a computerised design environment. Here, the concept that shall be employed is that which was provided in subsection 2.1.4, along the clarifications and distinctions with other computational elements related to aircraft design that were provided there. In particular, here we shall take in consideration the differences which were emphasised in the aforementioned subsection of computerised design environments with respect to standalone analysis software and MDO frameworks. In spite of these two aspects falling outside the scope of this review, their relevance in aircraft and RPA design is fully acknowledged, and they can even be integrated in current or future design environments, as it has been commented beforehand, and as it will be seen later on within this chapter. It is also highlighted that, according to the adopted definition of aircraft design environment, these must be of the GDM type, following the description of this type of design approach as laid out in subsection 2.1.3.

As mentioned in the introduction of this chapter, the review shall not only cover design environments specific of RPA, but also those pertaining to manned aeroplane design. Another key remark with respect to the scope of the review is that it will not only focus on design environments devoted to the conceptual design stage, rather, it will also consider design packages envisioned for use within other phases of the aircraft development process. As commented in subsection 2.1.4, design environments can cover any or various of the phases of the design continuum. Albeit the work developed in this thesis is mainly focused on the first stages of conceptual design, a broader analysis is considered appropriate for this review to provide a more holistic overview of this topical area. Furthermore, this will allow to contrast the current development state of design environments for the conceptual design stage when compared to those focused on other phases. In fact, previous works in the field of manned aircraft design have pointed out that most computerised environments seem to focus on optimisation and preliminary design (51; 76), with the conceptual phase being given comparatively less attention. This approach can allow to compare the distribution of works among various design phases with that which was conducted within the survey of section 2.2, allowing to compare with those trends, as well to reveal specific gaps which can be key to direct the efforts of the following chapters of the thesis. In view of the above, concepts related to further design phases, such as MDO frameworks and high-fidelity methodologies including CFD and FEA approaches, shall appear through this chapter.

When analysing the characteristics of the design environments, an additional hypothesis shall be considered regarding the possible differences in capabilities between geometric representation tools and physical modelling and analysis methodologies. There exist specialised CAD tools and geometry modules within many computerised aircraft design environments which present a notable flexibility in the definition of aircraft elements and configurations. In some cases, they can generate 3D models for unconventional layouts such as Blended Wing Body (BWB), joined wing or box wing. However, the fact that the geometry module can produce representations of these layouts may not imply that the other disciplinary modules contain the specific methodologies which are necessary to accurately analyse them. For example, the aerodynamic module may not be prepared to analyse the particular phenomena associated with a joined wing or box wing aircraft. This mismatch in capabilities can occur because design packages tend to integrate external software within their frameworks, as it will be seen later on this chapter. Therefore, it might be the case that the geometric module which is integrated in the design package (such as CATIA) is prepared to provide this capability, but the models pertaining to the aerodynamic module, which has been developed in-house or integrated from another tool, may not be able to adequately evaluate these layouts. Another reason for this capability mismatch may be that, since design packages are developed gradually, the possibility of representing geometries of unconventional configurations has been implemented before the associated analysis features. Therefore, in the case that the references do not explicitly express the capability of the other modules (aerodynamics, weight estimation, structure analysis, etc.) to evaluate these configurations, this shall be indicated in the trend analysis as a capacity limited to the geometric representation. This is according to the design package definition adopted in subsection 2.1.4, which emphasises features that can be leveraged within the design loop itself. The particular outcomes of this hypothesis shall be seen in section 4.5.

Having established the former hypotheses and scope, some aspects regarding the data gathering process to conduct the review are also commented here. A remarkable challenge in this process, as also underscored in previous research (91), is the fact that most of the design environments are proprietary, with the tools not being available outside of the developers' institution, or only through payment. Since the tools themselves could not be accessed during the development of this thesis, the information has been gathered instead by scrutinising their websites and documentation, when available, and also from research papers published by their developers in the open literature. This is a similar approach as that followed in previous research works in this area as cited in the previous section (59; 68; 63; 100; 91). Still, this procedure also presents a remarkable hurdle, which is that often, information about certain characteristics of the design environments (such as the presence or otherwise of a specific capability or module) is not explicitly provided in the references which have been consulted. This issue related to the lack of information about certain aspects of the design environments in the available documentation has also been faced by previous research (41). Considering the above, it is

also noted that the review conducted in this chapter has mostly focused on those design environments which are documented to a certain extent within the open literature.

Two more criteria shall be employed in the information gathering process. The first is that only characteristics which have been explicitly mentioned or demonstrated by the authors are considered to be available within a specific design environment. Finally, only capabilities which have been already implemented in the programs attending to the most recent publications have been considered, with future endeavours not being counted.

4.4. Current trends and challenges in computerised design environments

This section addresses the first of the three objectives of this chapter, which also constitutes the initial step in the overall study of computerised environments developed here. Its purpose is to highlight and analyse the areas of research within the field of aeroplane design packages which are experiencing a remarkable level of interest and development in recent times. Thus, the focus is not as much on individual design environments, rather on trends and challenges which can be seen through various packages, representing an overview of the general developments within the state-of-the-art. This will allow to capture an updated image of the current status of the foremost lines of work in this field of research.

As expounded in the chapter introduction, many of the developments and applications of computerised design environments are directed towards aiding the designer to tackle some of the main issues faced by the overall realm of aircraft design. Thereby, the challenges analysed in this section are also related to hurdles in the broader field of aeroplane design. Here, the perspective shall be particularly focused on the software tools themselves and on how they are addressing and advancing the possibilities of overcoming the related challenges within the wider discipline of aeroplane design.

As laid out in section 4.3, the information has been obtained from references within the open literature addressing the topic of computerised design environment development and analysis. As a matter of fact, many of the investigations in the open literature which seek to develop their own environments or to enhance existing ones start from an analysis of current hurdles, so as to then formulate potential ways and features that could be implemented in the design environments and which could aid to address these challenges. A similar approach is also followed in this chapter, as the evaluation of the overall challenges of the field conducted in this section will lay the groundwork for the analysis of the following one, which will turn its attention to the second objective of the chapter. In this way, from the findings of the overview of the main challenges provided in the review conducted here, a set of desirable features of design environments which can aid in addressing these hurdles shall be defined in the following section, leading to an evaluation of the current number of computer design environments which presently

showcase these features. To this end, for each of the lines of work expounded in this section, not only their current status in present-day computerised environments shall be analysed; but also the characteristics that, when implemented in the design package, could aid in surmounting the related challenges; as well as the most relevant approaches which have been employed up to date in this regard to improve the performance of these software suites within each of the identified areas.

An initial screening of the literature has revealed seven main areas of interest in aeroplane computational design environments which are being underscored in recent times. These are each expounded in the following subsections. It is noted that these seven areas are tightly interlinked to one another in several ways. These connections shall be highlighted along the text, and in the following section, a summary of these links shall be presented.

4.4.1. Knowledge-Based Engineering (KBE) capabilities

It has been acknowledged in previous works that aircraft design is a knowledge-intensive area (12; 95). This is due to many traits inherent to the design process, including but not limited to the high complexity of the tasks to be conducted, which as mentioned in the introduction to this chapter has increased in recent times; the intricate connections among disciplines and components; and the impact of decisions made during the first stages in the long run. Thus, design knowledge and experience play a significant role in the process of aircraft synthesis, and designers use their knowledge to ensure the effectiveness and efficiency of the tasks developed through the design continuum.

In view of the above, and as a means to enable to represent and to leverage the knowledge involved in the aircraft design process, in the last years the field of Knowledge Engineering (KE), also often called Knowledge Based Engineering (KBE), has gained traction within the area of aircraft design. The discipline of KBE is tightly linked with the field of AI (226), which is itself one of the main topics of this thesis. Depending on the viewpoint of each reference, KE can be considered as an area within AI (227), as a separate but related discipline (226), or even as the crossing point of various fundamental disciplines including AI and others such as Computer Aided Design (CAD) and computer programming (12). In any case, it is seen that the discipline of KBE is not isolate, rather it showcases relevant connections to other fields, particularly to that of AI.

Various definitions of KBE can be found in the literature. Consulting references within the general fields of AI and KBE, this latter discipline has been defined as *“the area of artificial intelligence that is concerned with the design, development and maintenance of agents that use knowledge and reasoning to perform problems solving and decision making tasks”* (227), and also as *“the process of developing knowledge based systems in any field”* (226). Moving to the application of KBE in aircraft design, the following definition was given in (228): *“KBE can be defined as a technology that allows capturing product and process multidisciplinary knowledge by means of integrated software applications that can automate the repetitive design activities, thereby reducing engineering design time and*

cost”, which may be extended to other areas of engineering design. These definitions emphasise, from various perspectives, the implementation of knowledge in software systems, which links with the notion and promising perspectives of employing KBE approaches within computerised design environments as it will be developed here further below.

From a practical viewpoint, KBE seeks to capture an abstraction of a reality, the knowledge of which is represented in a model. Using the field of aircraft design as example, these models can be, for instance, parametric models of a wing, or of other elements, since the parametrisation incorporates certain knowledge about the geometric dependencies and constraints of the entity. Another type of knowledge representation can be data models, which establishes a certain data structure representing facts and information of each of the elements of this structure. For example this could be the ensemble of different components of an aircraft and how they relate to each other, with this knowledge being manifest in a data schema of the properties of the aircraft and their association with its different components and systems. Design method and sequence knowledge can also be captured with these approaches (229). It can be seen that the models and applications of KBE are very diverse, which fits with the fact that knowledge itself can be of many kinds, as it will be explored in detail later on within chapter 5 of this thesis.

From a general perspective, the advantages that KBE applications provide can be noteworthy. For instance, in the work of (230), an evaluation of KBE applications in different industrial areas showed that these techniques managed to reduce development times in an order of magnitude, where processes which took months then took weeks, those which demanded weeks then required days, and so on. Within the field of engineering design, graph-based KBE methods can aid in detecting possible design conflicts among variables caused by distinct requirements (231). KBE has been noted as being particularly advantageous in aerospace, due to various reasons, such as the strict certification regulations that must be complied with, the long-life cycles of products and the large base of knowledge within enterprise and academia workers (72).

Moving on to the area of aeroplane design, many authors have highlighted the need to expedite the process by incorporating KBE methodologies in the design process (12; 72; 232). By implementing the knowledge concerning repetitive tasks within the design procedure, these processes can be automated (232), allowing the designer to employ more time in creative and analysis tasks (230). Knowledge management within the design process has also been recognised as a relevant issue (59). Improvements in interoperability between methods and software elements have also been highlighted, which is enabled by having a common conceptual model of the elements and methods that can be used through various applications, reducing the time involved in model matching tasks and interfacing (12). Additionally, as it will be further substantiated along the present section, novel KBE-based approaches have been remarked to hold great promise

for developing novel design and sizing tools focused on unusual air vehicle concepts (51). Furthermore, with the augmentation in complexity of aeroplanes which has been mentioned previously in this thesis, the interrelations amongst different components have become more ubiquitous. Therefore, approaches which allow to formalise these relations are becoming increasingly valuable within design procedures.

With the above, an overview has been provided on the field of KBE and some of its applications and advantages. A more detailed account of this area within the context of the broader realm of AI shall be expounded within subsection 5.1.1. More information on the theoretical basis, characteristics, applications, and advantages of the field of KBE from a broad perspective can be found in references (226; 230; 233; 234), and from a viewpoint focused on aircraft design, within (12; 235).

Now moving on to the specific use of KBE within aircraft computerised design environments, it should be highlighted that there has been interest in knowledge-based paradigms applied to computerised design environments for some time, as seen in the work of (229), where it was also emphasised that these efforts have historically focused to a larger extent on the preliminary and detailed design stages, with conceptual design being comparatively neglected. It has been recently when a larger interest has sparked in the development of KBE approaches for aircraft design which can potentially be integrated in computerised environments (12), and even in KBE applications for design packages themselves (232; 235). Below, some of the current approaches within this line of work are expounded.

(a) Knowledge-based geometry definitions and parametrisations

One of the most usual applications of KBE in engineering design is based on parametrization of models (230). This seeks to aid the designer in defining certain geometries by employing predefined algorithms and rules with which these shapes must comply (230). For instance, in aeroplane design, it would be costly to develop the model of a wing through a Computer Aided Design (CAD) software without previously implemented design knowledge, since in that case it would have to be defined from scratch through primitive operations such as extrusion, lofting, chamfering, etc. This is due to CAD software being generally more geared towards manufacturing than design (236). Nowadays, most CAD software is embedded with certain level of this technology, albeit for specific applications such as aerospace, particular KBE systems need to be developed (232).

If the knowledge concerning the design of a wing is captured, the designer can define a certain number of parameters, such as the wing partitions, their aerodynamic profile, and parameters such as aspect ratio, taper ratio and others which are typically employed in design activities. With this information, the system could automatically render the resulting wing through interpolations and Bézier curves, which are implemented in the underlying code (232). These strategies seek to capture the knowledge required to model

the geometry of the products, by establishing certain high-level abstractions which can be used as geometric “building-blocks” (for instance, aerodynamic surfaces, fuselage-like volumes, connecting surfaces, engines, etc.), each of which is defined by a series of parameters which can be easily defined by the designer (12). Moreover, the adopted geometric parametrisation and rules can be devised to be compatible with meshing procedures and CFD and FEM analyses, allowing for a seamless transition between different parts of the software suite and enabling parametric sensitivity analyses and optimisation. The above-mentioned approach has already been implemented in the CADLab design package (72; 232; 235), where it has leveraged the advantages mentioned above. The GENUS design environment has also implemented rule and knowledge-based geometry definitions and shape transformation algorithms (59).

(b) Common data models

As mentioned beforehand, knowledge can be represented through models establishing a data structure which contains various concepts and information pertaining to them. Following this perspective, one of the most extended knowledge-based approaches within the field of computerised design environments is that of developing and leveraging common data models within software systems. These types of models have received many different names, including: standardised/common data formats (237), standardised data models (238), data structures (232), data models (41), and data standards for tool integration (239), among others. The most outstanding examples of this application within this field are usually data schemas that define the elements, attributes, and structure of the information that can be contained within the data model, typically establishing a top-down decomposition of the air vehicle in several components at different levels of granularity, with each concept having a set of associated properties and further sub-components (238). Thus, the schema does not only contain knowledge about the information organisation itself, but also on the relevant variables connected to each concept, and it may even contain information about the methodologies and tools employed in the design process. This model can also be instantiated to store the information of specific aircraft (e.g.: Boeing 757, Airbus A330) with its corresponding values, and this can also be applied to aircraft concepts which are being designed. These data schemas are also usually compatible with parametric representations, thus linking with the previous point, as this eases changes in the geometry during the design process and their use within optimisation loops to perform recurrent calculations (237).

Aside from knowledge representation, one of the main purposes of a standard and uniform representation of data is that of establishing a common format which can be used through various tools (240). Thus, these models also serve as a shared language which ease communication among distinct software elements (238; 237), enabling standardised patterns for reading and writing data to be applied (41). Even if certain tools are not compatible themselves with the adopted data schema, the translation and interfacing process is facilitated, as the number of interfaces of the software suite have been reduced.

These aspects result in an improvement of interoperability among modules and tools used in the design package. Additionally, the fact that the data model can remain constant, even when changing or adding new tools to the suite, also enhances extensibility (41; 95). Advantages of this approach regarding data administration and knowledge management have also been highlighted in the state-of-the-art (41).

Some of the data formats developed in the field of aeroplane design environments are commented below:

- One of the most extended data formats in the field of aeroplane computerised design environments is the **Common Parametric Aircraft Configuration Schema (CPACS)**, an open-source data model implemented as an eXtensible Markup Language (XML) Schema Definition (XSD), which serves both as a central module and as a single language for interface connection (221). It started in 2012 (221; 237) and has been updated recently with more features (221). This format has been employed in computerised environments such as VampZero (237), CEASIOM (237), AGILE (92) and JPAD (241).
- The **Aircraft Design Markup Language for Multidisciplinary Aircraft Design and Analysis (ADML)** is another of such common data formats, also employing the XML syntax. It emphasises a bottom-up structure starting from constructs for functions and abstract mathematical objects, and has been specially tailored for unconventional configurations (240).
- The **Aircraft Design Data Model (ADDAM)** is an Object-Oriented (OO) knowledge-based data format developed alongside the Aircraft Design Box (ADEBO) computerised environment. It emphasises the use of standard rules such as parent-child relationships between concepts, uniform rules to model physical parts, unique part names to access data elements, and consistent interface procedures. It has demonstrated the capability of modelling unconventional layouts and RPA (41).
- Other computerised environments have also developed their own data models for use within their suites (232; 242).

The aforementioned CPACS, ADML, and ADDAM data models are compatible with conceptual representations for both the conceptual and preliminary design phases (41; 97; 240). It is noted that both CPACS and ADML, as well as certain internal data models used in other design packages, have employed the XML syntax, since it is both human readable and machine-processable (240; 221), and it has also been employed in data models within the broader field of aircraft design and MDO (12). The use of such mark-up languages to formalise the data schema and improve interoperability constitutes an advancement in contrast to earlier efforts where data was stored in documents, as highlighted in the work of (243). The relevance of data models within current

computerised environments can be such that requirements specifications for new design packages can contain many requirements related to the data model itself (41).

An example comparison between the different data structures which these models can present is showcased in Figure 4-2.

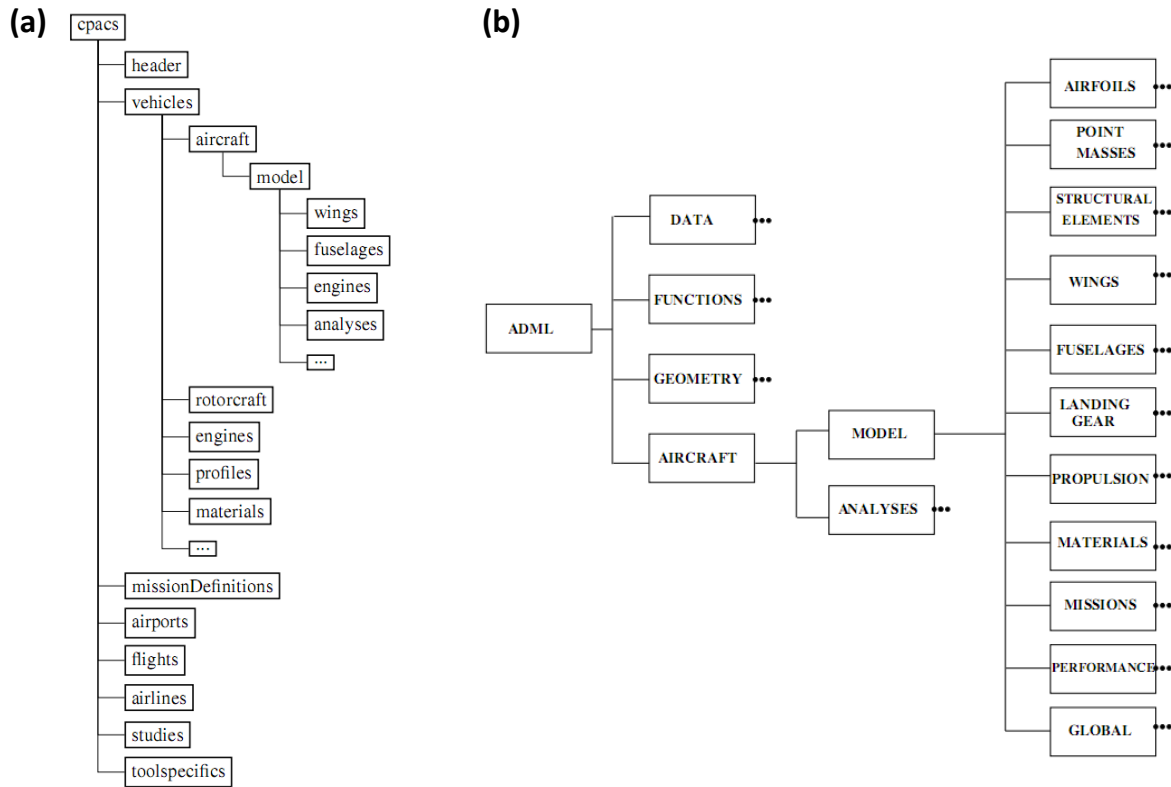


Figure 4-2. Example comparison between data schemas of two data formats employed in computerised environments. (a) CPACS, retrieved from (221), (b) ADML, retrieved from (240).

(c) Knowledge components

Another KBE approach observed the current state-of-the-art of aeroplane design environments is the development of knowledge components which encapsulate aircraft design and analysis methods and tools in such a way that they can constitute building blocks which can then be reused in different design workflows. This approach has been observed in the Knowledge-based and Extensible Aircraft Conceptual Design Environment (KEACDE) framework (95) and also in the ADEBO environment (41).

Albeit the approaches followed in each of them are different, the common idea is to start from a certain analysis or design method or tool useful for aircraft design or analysis. These can be design procedures already found within the state-of-the-art, for instance, the engine sizing method proposed by Raymer (14); tools such as AVL or XFOIL; or new in-house design approaches. With this, a definition is conducted of the “product data” managed through the method or tool, establishing the relevant concepts and variables as well as the mathematical or conceptual relationships among them, and identifying the

inputs and outputs. Then, a wrapper is generated which encapsulates the methods and tools alongside their require data, parsing their inputs and outputs to a format compatible with the overall data flow of the design environment. This consists in generating two add-on algorithms, one for the inputs and the other for the outputs, with the first one aiding to translate the information managed in the main workflow of the design environment to that which is required by the method or tool to operate, and then at the end of its internal process, a second algorithm translates the results again to make them compatible with the data model managed by the design environment. This allows to capture, formalise and reuse complex engineering knowledge as a series of “building blocks” that constitute a tool repository, and they can then be flexibly employed by the design environment as needed.

The aforementioned approach is comparatively novel and has yet not been used extensively in this field. However, the authors of both frameworks where they have been employed highlight the interoperability advantages, as once the wrappers are in place, the translation between the data model of the tool with that of the overall environment is streamlined (41; 95). Furthermore, there are also extensibility advantages, owing to a strict separation between tools and data model, as the design package can be expanded by adding further tools without modifying the overall structure of data schema (41).

(d) Other KBE-related approaches

The OO modelling approach, and in particular the Object-Oriented Programming (OOP) paradigm, are closely related to the field of KBE. The connections among these areas are extensively developed in references (229), (12), and (41), which are within the field of aircraft design. Considering this, the recent interest in following an OOP approach both in the development of new design environments (41) and also when enhancing and updating previous ones (229) would fit within this subsection.

An object in the OOP paradigm encapsulates data and data-access functions, and also inherits both behaviour and data itself from objects they are derived from, called ancestors (229). This allows to create a class hierarchy, where properties are inherited between objects following the defined schema. The objects can send and receive messages which invoke other objects or change their own attributes (41). The OOP approach provides several advantages which are relevant to computerised design environments, including making the design process more structure, and the methods more reusable (41; 229). Furthermore, it has been highlighted that the OO modelling paradigm may be promising for the development of novel sizing tools which are compatible with unconventional configurations (51). It is noted that parallels can be drawn between some of the above-mentioned aspects and concepts, such as establishing a class hierarchy and the encapsulation of functions, with those of previously commented KBE approaches such as data models and wrappers. The advantages of OO languages and programming have been highlighted in the development of design packages such as ADEBO (41) and GENUS

(59), and it has also been employed to enhance previous environments such as the Advanced Aircraft Analysis (AAA) program (229).

Another KBE-related approach is also mentioned here, which is the use of the Unified Modeling Language (UML). This is a standardised graphical language used to visualise, specify, and document the artifacts of a system through the concepts which can be used to describe it and the relationships between these concepts. It can be employed to represent distributed object systems such as those modelled through an OO approach, as well as for systems engineering, among other application areas. In the field of aircraft design, this language has been used in KBE approaches to represent the relationships and properties of aircraft components, such as those referred to the layout, components, and internal structure of an aeroplane (12). Graph representations of knowledge related to data and processes have recently been employed in order to support the organization and establishment of MDO procedures for aircraft design (97). Within the area of computerised environments, they have been employed to represent and document the concepts involved in OO approaches, such as in the ADEBO design package and its data model ADDAM (41).

As mentioned beforehand, knowledge management has also been highlighted as a relevant area within the aircraft design process (59). In the context of computerised environments, it has been noted that if there are no adequate documentation or knowledge transfer activities, this may result in a barrier to the evolution and continued improvement of these design programs. Particularly, if there is a lack of documentation, and proprietary tools which may not be accessible later on have been employed, the knowledge may not be reusable for future design efforts (59). Furthermore, knowledge management in distributed design environments is also a relevant issue (97), which shall be expounded in more detail in a later subsection of this review.

At the start of this subsection, it was commented that KE shares a strong connection with the field of AI. As it will be seen in chapter 5 of the thesis, which is dedicated to AI-related topics, AI agents often employ knowledge to accomplish their objectives, so many approaches seen within this trend could also be aligned with that field, which has its particular methodologies and models. There is a particular case within design environments which has placed a strong emphasis on leveraging AI-based methods, which is the package developed as a result of the project Artificial Intelligence supported conceptual Design of Aircraft (AIDA) (76; 244). This suite encodes knowledge based on analytical and practical procedures employed in classic aircraft design models and processes and leverages it through approaches based on both Rule Based Reasoning (RBR) and Case Based Reasoning (CBR) approaches. The capabilities of this package and the background on its methodologies shall be expounded in more detail in chapter 5.

Finally, there have also been previous studies which have proposed the use of ontologies and Semantic Web technologies for aircraft design and related disciplines. These approaches shall be expounded in detail in subsection 5.3.4.

(e) Summary

As it has been seen, there are currently various KBE-related approaches which are being leveraged in present-day computerised design environments. The common denominator among the distinct approaches seen above is that they all seek to formalise different types of knowledge which are usually in the designer's mind or in existing methods and tools. The purpose is to leverage this knowledge in different applications and to make it more reusable, with a particular emphasis on its use to automate repetitive tasks, so as to allow the designer to dedicate more time and effort to creative endeavours (12; 235).

One of the most remarkable aspects that can be highlighted from the review above is that these KBE approaches present noteworthy connections with many other areas which themselves constitute other trends and challenges in the field of computerised design environments, as it will be developed in further subsections. As seen above, they provide interoperability advantages, for example through the use of common data models; extensibility of the design packages can be enhanced such as when employing knowledge components; and they even show promise in the field of unconventional configuration design. These connections shall be explored in more detail within their respective topics. A relevant takeaway from this is that KBE capabilities can potentially serve as an enabler to enhance other relevant lines of work in design packages.

Finally, it is noted that the assessment of this trend does not only cover one of the main current areas of work in computerised environments, but it also serves as a key foundation for future developments in the context of this thesis, as it will be seen in chapter 5 dealing with AI topics in aeroplane and RPA design. KE as a whole shall be more thoroughly contextualised and developed within the field of AI in the chapter 5, introducing other types of approaches and models for knowledge representation which shall be among the focal points of that chapter. The application of KBE approaches in computerised environments is relatively recent and it can be expected that this area can still experience much development in the future, which is also one of the novel lines that will be explored in the following chapter, particularly regarding the use of ontologies to enhance the capabilities of computerised design environments.

Current methodologies: parametric design definitions, common data formats, knowledge components and wrappers, object-oriented programming, UML diagrams for representing components and their relations, ontologies and Semantic Web technologies.

4.4.2. Modularity, interoperability, and integration

As seen beforehand through the thesis, aircraft design is a multidisciplinary endeavour encompassing multiple disciplines that can be strongly coupled (91; 222). As already commented in subsection 2.1.4, computerised design environments tend to consider various design disciplines within their workflows, with their number and nature

depending on aspects such as the design stage being considered and the overall scope of the design package.

Lately, as it will be quantified in section 4.5, there is a trend of considering an increasing number of disciplines within computerised environments, thus broadening their scope. From the viewpoint of the program structure, these disciplines are usually organised in different “building blocks”, which can be either internal functions that encapsulate the models and calculations of a particular discipline or design step, as is the case of classic design packages; or they can even be full-fledged external analysis tools with varying levels of fidelity that have been connected or integrated within the design tool. It is key that these building blocks are structured and organized according to the user’s needs to aid in conducting the different design tasks (243). This abundance of design and analysis algorithms and tools leads to a preference towards a modular organisation of the disciplines and elements within the workflow.

The above-mentioned scenario leads to a variety of disciplines organised in distinct modules within the software, with these modules requiring to interchange information amongst them correctly and efficiently during the design and optimisation processes. The higher number of disciplines which is becoming the norm in present-day environments increases the complexity of information exchange in the system, even more so if external tools are to be reused, which also constitutes a current trend in this field. This requires paying more attention to interoperability and integration aspects among the modules, and also necessitates a larger effort in interface design. Thus, the tendency of design packages becoming more holistic in their scope brings to the forefront modularity and interoperability considerations, which have become more relevant in recent times, thus these aspects shall be analysed within the current subsection.

(a) Modularity

The practice of organising the disciplinary analyses within design environments in different modules is not new, and it constitutes one of the main defining characteristics of these software suites. This approach is mainstream within current aeroplane computerised design environments, as previous authors have acknowledged (51; 59; 86), and it has also been employed in other design areas, such as engine design (245). However, the current increase in complexity of computerised environments has increased the number of modules and tools involved (222), thus bringing more attention to this matter in recent times. Some of the foremost considerations and advantages in relation to this topic are commented below.

Organising the methods of the tool in a modular fashion allows for a more clear separation of the functions to be performed by the suite among the different modules. Each of these “building blocks” provides the intermediate data from a certain technical discipline, which at the same time connects to the inputs or outputs of other modules, with their adequate sequencing allowing to conduct the required sequence of computations (51). This

modular approach is preferred as it provides a more transparent design process (51), simplifies data exchange (51), enables to leverage to a greater extent the synergies among different disciplines (17), facilitates the development and testing of the package (51), enables the tool to be more easily updated (91), and allows to structure and organise the resulting modules in different ways according to the user's needs (243). It is also noted that modularity can also enhance computerised environment collaborative development and use in decentralised design teams (74), which is a topic to be explored in more detail within the next subsection of this review.

The advantages that this modular organisation provides in terms of flexibility have also been highlighted (17; 91), with this being one of the foremost desirable characteristics of design environments, as it not only provides several advantages of its own, but also acts as a key enabler towards other desired features. When considering at a broad scope the overall workflow of the design environment, and as also remarked by previous works, two kinds of flexibility can be considered:

- 1) **Flexibility at the discipline model level:** this refers to the capability of interchanging a certain approach or model with another one pertaining to the same discipline, thus modifying or replacing analysis blocks (91). For instance, a statistical sizing model could contain different correlations depending on various types of aircraft, as done in classic design manuals for manned aircraft (8; 48), and as also seen in RPAS depending on the powerplant type or other categories, which show notably different statistical trends (39; 40). This example refers to different approaches of the same accuracy, but the same principle can apply to models with varying fidelity levels. For instance, the aerodynamic module could allow to choose among a semi-empirical model, a panel method, an external connection to the AVL program, and an external connection to a CFD software. This kind of flexibility, which is usually supported by a modular approach, is one of the key enablers of multi-fidelity capabilities (17; 73; 91), which allow to select models of varying fidelity levels. In this case, due the remarkable differences in the input data required by the distinct approaches, other considerations regarding their inputs, outputs, and overall connection with the workflow should be considered. These points will be further developed in subsection 4.4.5. In any case, this process of swapping between different models can be seen when considering the overall design workflow as formed by a sequence of building blocks, with each representing a module, where the content of some of the modules can be interchanged with other types of models. Furthermore, this approach can also enhance the development of design environments which can consider unconventional configurations, as these layouts often require specialised analyses resulting in distinct models, even at the same fidelity level as the baseline ones (59; 60). Thus, maintaining the overall workflow but swapping the discipline models, the workflow can be adapted to perform the sizing of such layouts (59), as it will be developed further on.

- 2) **Flexibility of the overall workflow:** aside from enabling to change models within specific building blocks while using the same problem structure, modularity can also enhance the development of design packages which can organise these modules attending to different design or optimisation loops, adapting the overall design workflow itself. This can be a desirable feature specially when the environment must cover different design stages, such as conceptual and preliminary design, since the number of building blocks and their order may change. Furthermore, it can also be a crucial characteristic in the case of unconventional vehicle design when the design approach might require not only different models within the disciplinary modules, but also a rearrangement of the design schema itself, as seen in previous research (133; 155). As mentioned beforehand in the thesis, the organisation of the design workflow itself can be as important as the tools employed within it (51). This also applied to optimisation loops, which are usually employed in design environments, as it has been highlighted that the structure of the computation sequence must be carefully established to ensure adequate results (246). Thus, it is key that the design loop is adapted to the needs of the problem being solved. This capability has been shown in the design environments VampZero (89), AGILE (155), and ADEBO (41). For the last of these, the flexible workflow definition was even among the specifications of the package (41).

A comparison between both approaches as already seen in the GENUS and AGILE environments is showcased in the following figures: **¡Error! No se encuentra el origen de la referencia.** shows an exmple of method flexibility while keeping the workflow, corresponding to the GENUS environment. In contrast, both Figure 4-4 and Figure 4-5 correspond to two distinct workflows in the AGILE paradigm, where it can be seen that they have changed depending on the aircraft layout which is being studied. The first case represents a loop applicable to the conceptual design stage, whereas the second constitutes a MDO scenario. This showcases the applicability of the aforementioned concepts to design processes corresponding to different stages of the design continuum.

As seen above, the flexibility ensuing from these two possible approaches enables the enhancement of the possibilities and characteristics of design environments, with the potential improvements in terms of method flexibility and unconventional vehicle design being of particular interest here, as they link with other trends analysed later on in this survey. These aspects are also connected to the two limitations (applicability and scalability of current methods and tools) and the two main areas of interest (capabilities of the implemented design methods and their workflow) as commented in the chapter introduction, as this modularity aids in extensibility aspects, can allow to reorganise the workflow of the analyses, and also enables to integrate further methods which can expand the applicability of the baseline environment.

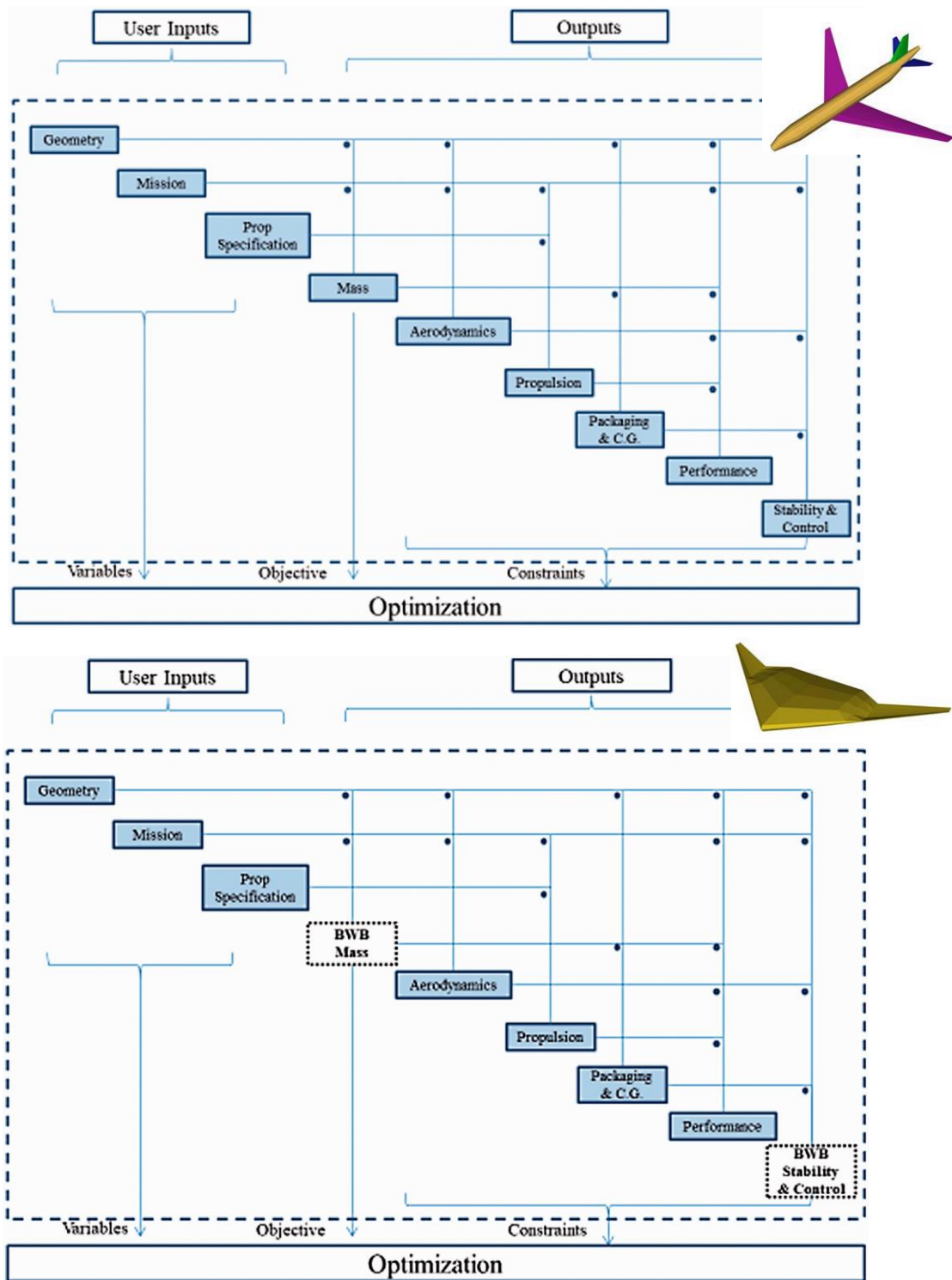


Figure 4-3. Example of flexibility at the discipline model level, corresponding to the GENUS environment. The upper image corresponds to the generic case, and the lower one to the BWB design, where mass estimation and stability modules have been swapped. Images obtained from (59).

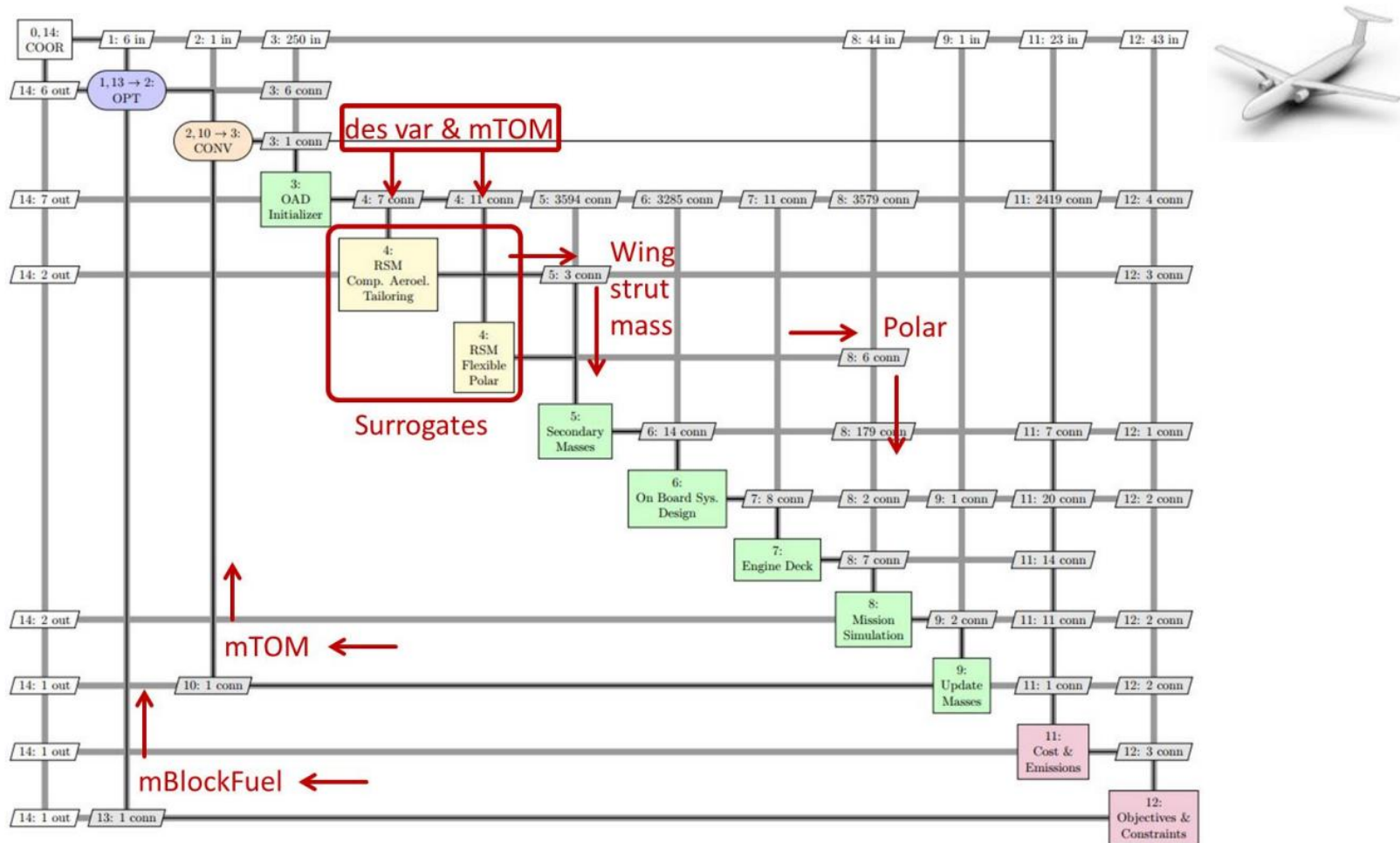


Figure 4-4. Example of flexibility at the workflow level, corresponding to the AGILE environment. The workflow presented here corresponds to a truss-braced wing aircraft. This image is complemented with the one below to showcase the change in the workflow. Images obtained from (155).

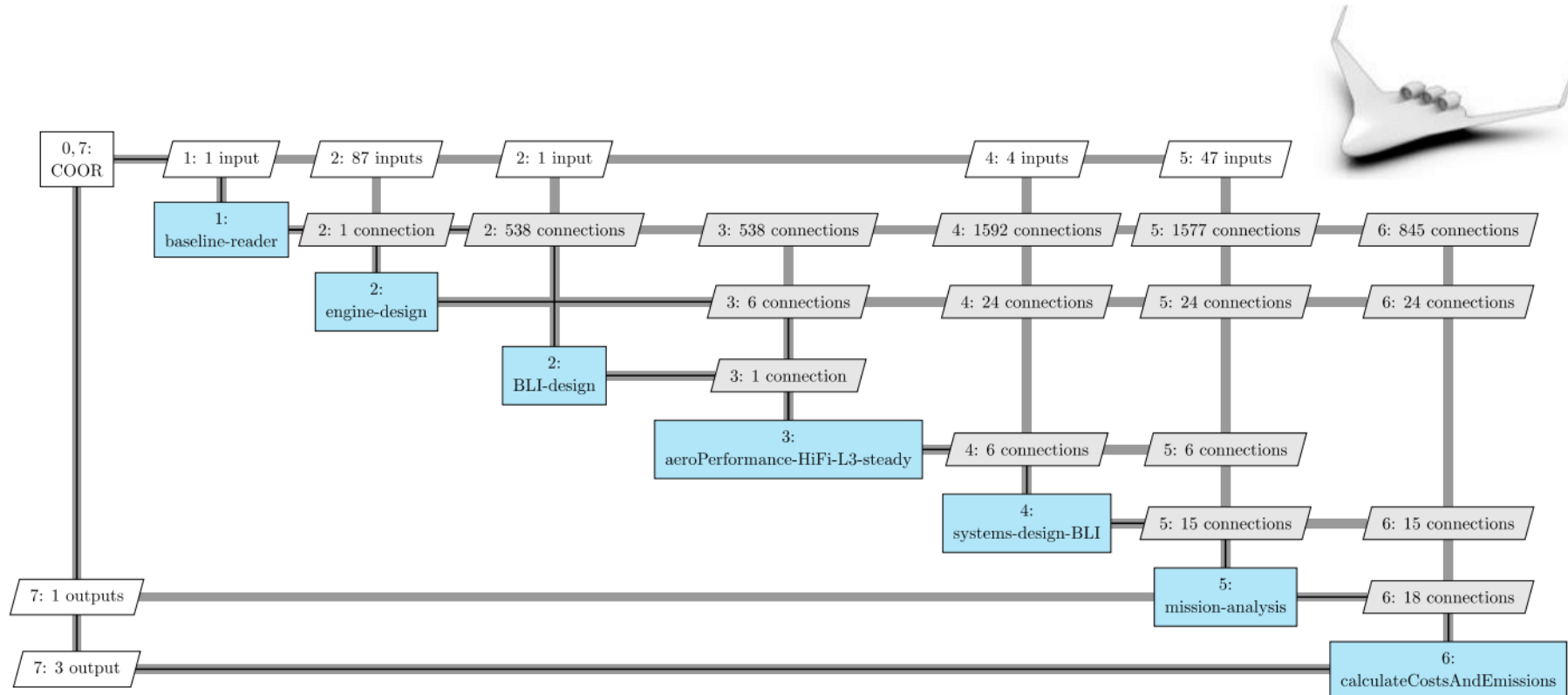


Figure 4-5. Example of flexibility at the workflow level, corresponding to the AGILE environment. The workflow presented here corresponds to a BWB, with the overall structure of the workflow being different than that of the preceding figure. Images obtained from (155).

With the recent increase in the complexity of computerised environments, modularity is among the main features which has been remarked as a key requirement in the development of new design packages, since it allows for greater flexibility and extensibility when developing and updating the design environment (91). However, the multiplicity of modules leads to an added effort in establishing appropriate interfaces among the modules involved, so as to ensure seamless interoperability. Thus, this leads to the following topics developed below.

Overall, this increased flexibility enables the exploration of a larger design space, as well as the study and comparison of distinct possible layout alternatives, thus also enhancing trade studies between diverse configurations (17). This comes as a result of the modules being able to contain different methods of varying scope, which are compatible with each of the aircraft types. At the same time, these distinct models can share similar input and output architectures, allowing them to be swapped within the overall workflow to adapt to the configuration being considered in each case. As expounded beforehand in this thesis, the capability of exploring a large design space connects with one of the main objectives of the conceptual design stage, as developed in subsection 2.1.2. It is brought forward here that the method flexibility approach shall be applied to the development of the novel design methodologies to be developed in part III of this thesis so as to account for variations in the models attending to different RPA layouts.

In many cases, a central module, control program, or management layer is used to coordinate the individual module organisation, data exchange, and evolution of aircraft concept geometry (51). This can be seen in many state-of-the-art design frameworks, particularly in those more focused on optimisation, such as KEACDE (95), AGILE (74), or RAMP (61).

(b) Interoperability and integration

The issues of data exchange and interoperability within aeroplane design environments have been studied since the times of the first design packages (243), where usually computing architectures were employed to aid in the communication between the different modules. Even nowadays, the topic of data format of flow is among the foremost challenges in this area (59), with data inconsistency and also the potential discrepancies between inputs and outputs of different design steps being among the issues which are being studied in recent times (73). Furthermore, the use of external software as specialised modules of the design process, which adds a further layer of intricacy to interoperability matters, has also been a sought-after characteristic since the inception of the first design environments (243).

Nowadays, there is a growing trend towards more holistic environments with a higher degree of modularity; the use of various external tools, with these even being from different vendors (100); and some design frameworks are being conceptualised as combinations of previously existing analysis tools, even reusing previous design

environments. As mentioned beforehand in this thesis, MDO loops are usually integrated within these design environments, and it has also been highlighted in this area that Additionally, there is also the need to establish adequate interfaces with other elements aside from disciplinary analyses which are also included in current design environments, such as lookup tables (17), and also aerofoil, engine, and component databases (35; 61; 95). Furthermore, ensuring seamless interoperability becomes an even more critical matter in the frame of collaborative and distributed design environments (70; 221). All of these aspects can be expected to demand a higher effort in interoperability considerations in the present landscape.

Even if the aircraft concept which is being progressively developed along the design continuum is the same in all cases, different discipline models (aerodynamics, structural analysis, etc.) might require distinct abstractions of this same concept attending to each of their needs and perspectives (12). Thus, the need of translation to provide the data required by each module is one of the main issues related to interoperability matters.

A different translation effort may be required for each of the interfaces of the model, which can be considered a measure of the interoperability complexity of the software environment. Thus, an increasing number of modules also brings forth higher complexity as the number of interfaces increases. In previous works, it has been highlighted that the maximum number of possible interfaces among modules (221), should every module require connection with the rest of them, rises according to the law:

$$Interfaces_{max} = N_{modules} \cdot (N_{modules} - 1) \quad [4-1]$$

where $N_{modules}$ represents the number of modules in the program. The above expression already account for two-way communication and interfacing. As it can be seen, augmenting the number of modules of the environment leads to a noteworthy increase in interfaces, which can be unmanageable if a large number of modules are included, which is according to recent trends in design package development as mentioned beforehand. This necessitates new approaches to manage the interfacing efforts.

Depending on the way in which modules are employed in the overall computerised design environment, modules can be considered to be either internal or external. Internal modules tend to be those algorithms implemented in the core of the design package. New analysis and design models developed in-house by the team developing the design environment usually fall within this category. Then, there are external modules, which are typically medium or high-fidelity software developed by other entities and focused on a single discipline. These may include, for instance, software such as Tornado to perform aerodynamic calculations, JSBSim for flight dynamics and control simulations, or FLUENT and NASTRAN for high-fidelity aerodynamic and structural analyses, respectively.

The extended use of external software represents a current trend within the development of aeroplane computational design environments, which has been motivated due to

various reasons. One of these is that aircraft design tends to seek the use of well-established tools and methods so as to benefit both from their acknowledged results and also their high level of specialisation (41). In such a way, these external software usually present a very high level of development and maturity in each of their areas, motivating engineers to employ them to perform specialised calculations instead of programming a proprietary analysis module from scratch (55). This leads to reduced module development time, thus allowing the computerized design environment to focus more on the aeroplane sizing and optimization workflow and on managing the different processes. Additionally, capabilities not available within the core design package can be integrated in this way (100). Another reason for the use of these external programs is the need to incorporate higher fidelity analyses depending on the scope of the design process, for instance to perform the design of unconventional configurations (85). This is related to the trend of multi-fidelity analyses as it will be discussed later on. Furthermore, some design environments can also be connected to optimization packages, in such a way that the aeroplane design software works as a function with multiple inputs and outputs, which is managed by an external optimizer (247). There are even cases in which certain modules of some design environments are used as components of other design packages (248).

In contrast to the aforementioned possibilities and advantages, there is an added effort which must be undertaken to connect the design package to these external programs through properly designed interfaces. To automate this task, wrappers, which were already introduced in the previous subsection, are usually required to translate the data format of the external software to the one employed by the design software (100; 238). The use of common data representation formats such as CPACS, ADML, or ADDAM, which was also a concept introduced beforehand, can further ease the automation of these tasks and allow the coupling of the design package with external specialized tools (221). These data formats can even be used as a central module to further enhance interoperability, which is an option developed further below. A modular organisation of the design environment constitutes a further aspect which has been noted to ease the aforementioned tasks (59; 243).

Seamless interoperability amongst the core design environment and different external disciplinary analysis tools has become one of the main efforts within aeroplane computerised environment research. Many current design packages incorporate some degree of software synergy. Most of these interfaces are established either with geometric modelling tools (90; 223) or with high-fidelity software such as those focused on FEA or CFD modelling (85; 87; 223).

Albeit a distinction has been made beforehand between internal and external modules, it might be considered that the latest trends in this field have somewhat blurred the frontier between the two aforementioned categories. Some recent design frameworks, even if they have also developed their new in-house models, have been developed with special

emphasis in the seamless connection among previously existing tools and methods (17; 41; 92). In these cases, these tools are integrated as building blocks within the workflow of the design environment, thus behaving more as internal modules rather than external ones. The above-mentioned classification might also be blurred when the design environment has mainly been developed through integration of existing approaches and novel modules within integration frameworks such as ModelCenter (17; 222), as in this case the encompassing frame has not been developed in-house, but it is constituted by the framework which is employed to combine all of the modules. In any case, most of the current approaches to enhance interoperability which will be commented further below can be applied both to internal and external modules.

In spite of the effort required to ensure interoperability within design environments, particularly considering the recent trends in this area, there are many noteworthy advantages which can be achieved if a seamless integration between modules is ensured. Beforehand, the specific advantages of integrating external modules within the design environment were expounded. In contrast, the account provided below considers the advantages of enhancing interoperability and integration within design environments from a broader perspective.

One of the foremost advantages of enhancing interoperability aspects is that the development of design environments integrating a wider range of modules and other elements becomes more readily feasible, which fits with one of the current trends within this field. A robust interoperability and translation framework can also aid in solving couplings among different disciplines (17), thus enhancing an efficient organisation of the design workflow. Another efficiency advantage comes from the fact that translations among different model abstractions can be automated to a higher degree, which reduces the time which the designer must dedicate to manual interfacing and model preparation (70). It is noted that these kinds of tasks (which may include, among others, preparing a geometric model for CFD meshing), which are more usual in the preliminary and detailed design stages, were already mentioned in subsection 2.1.2 as being particularly time consuming, with many still requiring a large degree of manual input (10; 73). Thereby, advancements in this regard can expedite the design process and allow designers to dedicate their efforts to more productive and creative tasks (12; 243). Since many of the tools requiring more laborious inputs preparation are those of high-fidelity software, improving these aspects can also enable a larger deployment of multi-fidelity approaches, which represents another key trend to be analysed in detail later on (41; 73; 91). Furthermore, as it will be developed in further detail within another subsection of the review, it has also been highlighted that higher interoperability can be a key enabler for the design of unconventional layouts. This is not only due to the aforementioned parallel increase in multi-fidelity capabilities (55), but also as a result of improved framework extensibility, overall method flexibility, and the enhanced capability of the environment to manage more coupled analyses, which have been noted as being needed in many unconventional layout design cases (86).

All of the previously mentioned advantages of enhancing the interoperability capabilities of design environments have led to research on potential ways through which this can be achieved. Most of the efforts are related to ensuring a more straightforward translation between the models and data schemas required by different modules. As commented beforehand, distinct models usually require dissimilar abstractions of the aircraft conceptual model, so even if there is a single common concept representing the design, each discipline requires a different model representation which must be consistent with the overall abstraction (12). The main areas of work also seek to reduce the number of interfaces in the overall framework, as this decreases the amount of effort to be dedicated to translation and interfacing, which when combined with more efficient and seamless translation, can result in a fundamental asset particularly within environments that have numerous modules. All of this has resulted in the main lines of research in this regard seeking to establish a central node which communicates with all the other modules, concentrating data representation and translation efforts at this point. Three main ways of putting the above-mentioned notions into practice have been found, which may also be used in combination:

- 1) **Geometry-centred approach:** within aircraft design integration frameworks, it has been highlighted that a central CAD representation can not only serve to aid in visualising the aircraft model, particularly in later design stages where more information on the geometry is available, but it can also to provide parametric information to other tools, such as those performing FEM and CFD calculations (100). This approach has been observed in current design packages, with these employing a central module which controls the evolution of the geometry of the aircraft during the sizing or optimization process (61; 232), thereby serving as a common node to which the rest of the specific modules are connected, thus reducing the number of interfaces within the system. Within this approach, the software which manages the central geometric model usually incorporates meshing capabilities, amongst others, to provide the means of connecting with different analysis tools. The geometry is updated on each sizing or optimisation iteration, and the analyses are run again with the updated geometry until convergence occurs. Previous works have emphasized the need of a robust parametric model to represent the geometry of the aircraft which can adapt to the changes in layout sought by the optimiser (12), which links with the KBE approaches expounded in the previous subsection.
- 2) **Database-centred approach:** as mentioned beforehand, computerised environments may integrate databases which can contain varied information that can be called in different analysis modules. A possible approach to enhance interoperability is to establish a central database, which can be programmed on the Web to make it available to decentralised team members (95), which is particularly relevant within collaborative and distributed environments (70). This database can store a geometric model such as the one commented in the previous

approach, providing synchronisation between the efforts of different teams members, and updating the model as required (70).

- 3) **Central data model approach:** this involves the use of common data models such as CPACS or ADML, which were already introduced in the previous subsection, as a central node within the design environment. As mentioned beforehand within the current subsection, these data formats can be employed for translation at the different module interfaces. Taking this a step further, they can be employed within a central node to concentrate the representation and translation efforts of the whole environment. This enables the central data exchange of the design package to be expressed in the common format, allowing to exchange only input and output data between each tool and this central node. Albeit translations must be established between the common data model and each module which is not natively compatible with it, the number of interfaces is remarkably reduced. This data-centred approach has also been employed in other areas of aviation design, such as aero-engine design (175).

Using the aforementioned approaches, and particularly the third one which also establishes the data model as the single data exchange format of the whole tool, the interfaces of the system can be reduced to just the ones between each module and the central data format, with ideally no interfaces being present among the modules themselves. This modifies the law which gives the number of interfaces as a function of the number of modules to the following expression (221):

$$Interfaces_{central} = 2 \cdot N_{modules} \quad [4-2]$$

Where the number of modules is multiplied by two to account for two-way communication and interfacing, as in the case of the previous law. Figure 4-6 represents the two possible interface configurations when following the laws given by equation [4-1] and [4-2]. As it can be seen, the improvement in interface efficiency is more remarkable as the number of modules involved in the design environment increases. This does not only support the investment of effort in applying the solutions commented above for design packages which cover a wide range of disciplines, but the use of one of these approaches can even become a requirement when dealing with very involved and holistic design environments with a large number of elements. Considering the trend of the increasing number of modules and sophistication of design packages, the recent emphasis on the aforementioned interoperability efforts it can be explained, and it can also be expected that the use of common data formats shall become more extended in the following years.

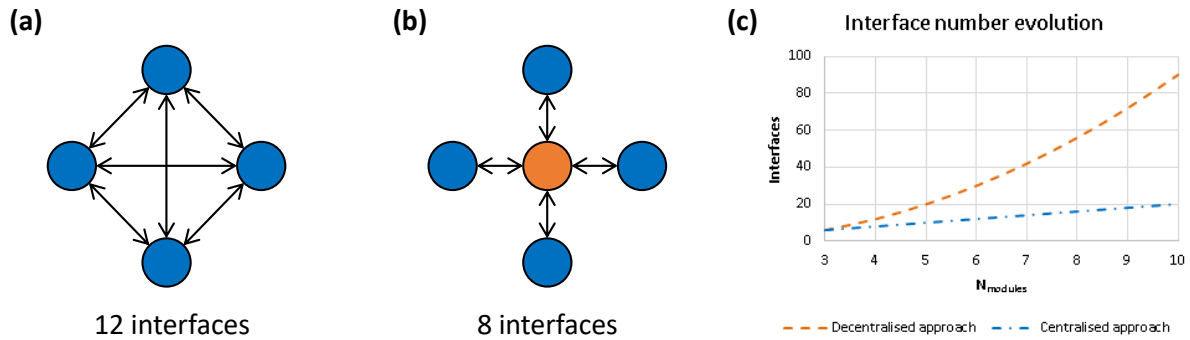


Figure 4-6: comparison between interface evolution depending in the number of modules. (a) for 4 modules, 12 interfaces when following a decentralised approach, equation [4-1], (b) 8 interfaces when following a centralised approach, equation [4-2], (c) the gain in interface efficiency is more remarkable when the number of modules in the environment increases.

(c) Summary

As seen beforehand, the increase in the complexity of design environments in recent times is leading to a larger emphasis in modularity aspects, which is in turn also moving interoperability and integration issues to the forefront of research in this area. There have been noteworthy advancements in this regard, with various approaches to argument interfacing efficiency which are mostly based on the use of a central node for the whole system, following three distinct approaches as seen beforehand.

It can be seen that the efforts in these areas also result in several advantages in relation to other current trends and challenges in the field of aeroplane design environments. As seen above, the flexibility which is allowed by a modular approach can enhance the integration of several models for the same discipline, enhancing extensibility, as well as method flexibility and multi-fidelity capabilities (73). These aspects are also improved through interoperability efforts, since the integration of external tools to the package, including those of higher fidelity, is also enhanced. Moreover, advantages regarding unconventional vehicle design resulting from modularity and interoperability efforts have also been highlighted (91; 55). Furthermore, both of the lines analysed here can also result in facilitating the deployment of distributed and collaborative design environments (70; 155). Thus, the aspects studied here can be key enablers for other relevant trends and hurdles presently being dealt with by design environments, as it will developed further on within this review.

Current methodologies: organisation of design environment elements in modular components, wrappers and translators for external software interoperability, common data representation formats for interface translation, use of central node to centralise interfacing and translation efforts.

4.4.3. Design in distributed and collaborative environments

Aircraft design has always been a multidisciplinary and collaborative subject, where experts from different areas and organisations cooperate to achieve the desired results (70; 249). This was already brought forward in subsection 2.1.2, where some examples of the diverse disciplines which intertwine in the synthesis process of an aircraft were seen. It was also commented that the number of these disciplines as well as the fidelity of their associated analyses tend to increase along the design continuum. The design process is not only a matter of arranging the models of different disciplines in an effective workflow, which in itself is a crucial task (51), as it has been commented in the preceding subsection on modularity. It is also key to organise the work of the different specialists in relation to their disciplines and responsibilities. Thus, topics of collaborative engineering have been the subject of much research in engineering design (70).

However, the current context of aeronautical research and product development results in a series of hurdles towards organising the responsibilities and tasks of different experts within an overall collaborative project workflow. Firstly, it is noted that design teams are often disseminated through the globe within different organisations, particularly in the case of research consortiums or large aerospace design collaborations (70; 249). In many cases, the distinct organisations involved in the same design endeavour also have different areas of expertise, thus leading to specialisation not only between experts but also at the organisation level (249). These aspects do not only imply that experts on dissimilar subjects are located at different places, thus difficulting communication, but also that computer systems and software elements are decentralised (249).

As a result, another layer of intricacy is added to the task of organising design workflows that not only involves distributed experts but also hardware and software elements, which in the latter case might not be transferrable to other computers. Aside from organisational complexities, this scenario establishes additional hurdles in matter of interoperability, which are added to the challenges commented in relation to this topic within the previous subsection. Now, a potentially greater number of software elements, which are also from diverse stakeholders, are being considered (249), augmenting the effort required to ensure interoperability, which must not only be observed among tools but also from a cross-organisational viewpoint. A further issue arises in that the timeline of tools run time sequence has to be carefully considered so as to avoid inefficiencies in the process. This requires taking into account not only the design process workflow, including the dependencies between software elements, but also the run time of each of them. Some analyses can be run in parallel to improve the overall efficiency, but this requires further careful planning to ensure a proper sequencing of the process (222). Relevant issues regarding file and information exchange in distributed environments also arise within this paradigm (70).

All of the aforementioned hurdles are aggravated when considering the increase of complexity in current aeronautical products, and thus in design procedures and

environments themselves (17; 41; 100), as anticipated in the introduction to this chapter. It has been noted that the increasing level of detail required to design and develop current and future aircraft, which present higher intricacy (218), require greater levels of specialization at human and company level. This does not only lead to a rise in the number of experts involved, but also in the quantity of software tools and elements, which must also cover a wider array of disciplines so as to enable to address these more involved design procedures (222; 249). Additionally, when later design stages are being considered, the greater number of disciplines and the increasing complexity of the analyses further augment the number of experts involved, as well as the number of software components required, thus difficulting to a greater extent the effective organisation of the collaborative aircraft design workflow.

Overall, it can be seen that many of the current trends not only in the field of aircraft design environments, but also in the broader realm of aircraft design itself, result in design teams being larger and scattered, and a greater number of design tools from decentralised stakeholders being required. All of this leads to remarkable hurdles in ensuring seamless collaboration among people (human-human communication) and interoperability among machines and software elements (machine-machine communication), thus resulting in an increasing importance of managing the human and computational resources efficiently within the design project. This supports the fact that the attention to distributed and collaborative environments for design is among the main trends discussed within the present review, as it has become a pressing topic in the later times.

In spite of the aforementioned challenges resulting from this paradigm, the potential benefits that can be leveraged from a collaborative and distributed approach towards aircraft design activities support the effort which is being dedicated to this area. As mentioned by previous authors, organising teams of experts and even enterprises which stand out in different areas can allow to combine the best possible technical expertise for the diverse design activities (70; 249). The creativity and potential synergies which might arise from such diverse teams have also been highlighted (70). The need to overcome the aforementioned hurdles, combined with the promises of the advantages that distributed and collaborative design can bring, have led to many efforts in this area, with different tools and certain recent computerised design environments incorporating capabilities related to workflow management and collaborative design, so as to enable decentralised and cooperative design processes (70; 92; 221). Some of the outstanding recent lines of works and efforts in this area will be commented below.

(a) Use of common languages and standards

As highlighted in previous research on computerised environments, the deployment of MDO systems has evolved from monolithic frameworks which conduct several analyses all on the same computer, to a distributed scenario where different computers each perform specialised analyses and they are connected to a central workflow, on to the

current paradigm consisting of not only distributed analyses but also competences among teams of specialists (155; 249). The models and vocabularies employed by different stakeholders can at times be starkly different both in syntax and semantic aspects, which can difficult compatibility between tools and discipline abstractions (249). Thus, it has been noted that sharing a common language across different models and stakeholders for data exchange and model description is crucial in the current context (249).

In this context where human-human and machine-machine communication is crucial to ensure effectiveness and efficiency, the standardised data formats such as CPACS and ADML which were already discussed in previous sections, play a key role. As a matter of fact, one of the main purposes of the development of CPACS was to establish a common format which could not only enhance machine-machine communication (interoperability) but also a common schema to aid in human-machine and human-human common understanding, particularly when different organisations were involved in the same design efforts (238). This ensures that all stakeholders use the same data format, easing data interoperability and exchange (221). The advantages of common data formats in this regard, as well as the increase in design team efficiency, have been highlighted in previous works within the area of aircraft design packages (59; 221; 238). Aside from design packages themselves, it is also noted that other XML formats have been employed in the realm of analysis and simulation software, such as the Dynamic Aerospace Vehicle Exchange Markup Language (DAVE-ML), highlighting this trend in other areas of aeronautical engineering (240). The emphasis on communication and interoperability matters seen above shall be a key point of the research to be conducted on AI further on in chapter 5.

(b) Deployment of integration frameworks for distributed tool integration

Another main line of work towards enhancing collaborative and distributed design is focused on the development of platforms which allow not only to organise the workflow of the involved tools in the design process, but also to manage their run time sequence, invoking each of them at the proper time, and also automating the data exchange, loops, and iterations among them (100). These are usually called “*integration frameworks*” (100; 222). One of such tools is the Remote Component Environment (RCE), which has been developed at the Deutsches Zentrum für Luft-und-Raumfahrt (DLR) (222). This environment allows to establish a certain workflow including tools and software located at different participants’ sites. This allows to set up a distributed simulation and analysis flow by integrating the different tools into a peer-to-peer network. In a MDO process, it is usual that different participants have access to diverse tools and modules, which perhaps even work on different operating systems (222). By allowing the tools of different teams to be interconnected in an automated manner, expert and tool management can be facilitated, and design synergies can be more adequately exploited. Other integration frameworks such as ModelCenter, OpenMDAO, and ModeFrontier, have been reviewed in the work of (100).

It should be noted that these tools would not constitute computerised design environments by themselves according to the definition used in this work. This is because they do not contain within their own core the models and tools used to tackle the design of a product. Rather, they establish the computing and interaction architecture on which different tools can be placed and connected, depending on the type of problem being solved. Thus, they act as an enveloping framework and key enablers towards the deployment of decentralised computerised environments themselves. In particular, ModelCenter has been employed to establish the optimisation frameworks within the KEACDE paradigm (95), in a similar way ModeFrontier has been used in the CADLab package (232), and the RCE platform is one of the key elements enabling the AGILE framework, as it will be commented below (249).

(c) Application of collaborative approaches in aeroplane design packages

The AGILE Consortium represents one of the most successful efforts in distributed and collaborative aeroplane design environments (96). The paradigm developed within the frame of their project has been defined in other works as a “development framework” (59), consisting of a set of technologies which allow MDO to be conducted collaboratively in distributed and heterogeneous design teams, achieving time reductions in MDO efforts of around 40 % with respect to previous efforts (96). This project involved a wide consortium of industry, research, and academic partners, thus addressing cross-organisational interoperability and collaboration was key towards achieving their purposes. To enable the integration of tools from different stakeholders in an organised and automated manner, two different integration environments were adopted: RCE and Optimus (92; 249). More details on the assimilation of these environments within the AGILE framework, including architectural and computational aspects, can be found in (74), with some examples on the complex design problems which were tackled in this distributed and collaborative manner being expounded in (155; 222). Furthermore, the AGILE paradigm has adopted the CPACS data format as the main language for model representation and data exchange, with several advantages as discussed through the past subsections. Another design package and integration framework assimilation example is demonstrated in the use of OpenMDAO within the Computational Research and Engineering Acquisition Tools and Environments – Air Vehicles (CREATE-AV) effort, as developed in (242). Therefore, it can be seen that the use of integration frameworks as platforms for collaborative and distributed workflow management within computerised design environment has given outstanding results in recent times.

Other collaborative efforts can be seen in different design packages. One of the main priorities of the RPA design environment CCADE, which was developed in the context of aerospace student collaboration within an educational context, was to establish a collaborative environment that could be used by students from different institutions. The sharing and synchronisation design information and analyses results was enabled through the use of a central database system established on the Web (70). Within the

framework of KEACDE, a database approach was also employed to ease collaboration through the use and sharing of the knowledge components developed within this paradigm, as expounded in subsection 4.4.1 (95). Other design packages such as ADEBO have emphasised collaboration and concurrent engineering among their specifications (41). Finally, it is noted that this collaborative design paradigm is also being increasingly taken into account nowadays in other areas such as aero-engine design (245)

(d) Summary

The trend analysed here mainly fits within the second main area of interest as laid out in the introduction, which was that of software architecture and computational workflow aspects. It can be seen that this trend has a tight relationship with the ones developed beforehand. In fact, many of the current approaches that can aid in tackling the issues of interoperability and integration are also greatly beneficial for the challenge of distributed and collaborative design. The use of common data formats is relevant to both the areas of interoperability and KBE, and it is also an essential asset in the current trend, as supported by previous research (59; 238), and these paradigm has already been put into practice in computerised environments (155; 249). Modularity also presents relevant links to this subject, as it also enables the different discipline analysis algorithms to be distributed through a collaborative network, and even easens their development by assigning programming tasks to different specialist entities. However, additional considerations to these previously studied paradigms are also required to enhance collaborative and distributed design, such as seen beforehand in the deployment of integration frameworks such as RCE, ModelCenter and ModeFrontier, which have been used to great effect in present-day design environments.

Current methodologies: common language and data formats, remote tool combination within networks using integration frameworks, Web-based technologies for data management.

4.4.4. Framework extensibility

Considering the evolving trends and hurdles in the field of aircraft design, the possibility of updating and improving current tools with new methods and capabilities to face these new challenges can be considered a promising prospect. For instance, the use of computerised environments to design unconventional configurations and RPA was not as extended in previous years, being a relatively recent endeavour which is nowadays increasingly relevant in this area. Therefore, the development and implementation of novel methodologies and approaches in design packages is required. This can be done either by creating novel frameworks or by updating current ones.

The first option can constitute a lengthy and costly process, so the second one can be considered a promising prospect. However, there are various challenges which must be surmounted in order to carry out this alternative. As a matter of fact, this topic links with

the second type of limitation of current aeroplane design frameworks as highlighted in the introduction, which was that of flexibility and scalability. Existing design packages with scarce modular organisation of the workflow and many internal and external interfaces present more difficulty towards expanding their capabilities beyond the originally intended ones, therefore not being as suitable to face the new challenges that aircraft design environments are facing (247). For instance, it has been noted that the analysis of unconventional aircraft requires more modules covering a wider array of discipline and a tighter coupling among existing ones (247). This high complexity and interaction between analyses and tasks would require significant changes to existing codes which present the aforementioned characteristics, difficulting their extensibility.

Thus, it is key to discover ways through which framework extensibility can be improved, as this will not only enable the update of the environment to implement new methods which can cover novel challenges, making them more adaptable to the evolving challenges in the field of aircraft design, but also to consistently update and improve it when new paradigms or tools appear which can improve its effectiveness and efficiency. This has established the interest in framework extensibility as one of the recent trends and efforts in this area.

From a broad perspective, extensibility can refer to the capability of the code to grow in such a way that there are no significant changes required to the underlying structure and data flow (247). This capability is key, as the lack of extensibility of previous design software has led to the need to develop new ones which present this capability (59; 86). Furthermore, many design environments seek to increase their capabilities over time, such as GENUS which integrated a Radar Cross Section (RCS) module in one of its updates (153) and envisions future compatibility with CPACS (59), or the framework for RPA design developed in (17), which sought to add new models and tools to offer enhanced flexibility in future revisions. Extensibility can also improve the evolution of the design package to cover different design stages (68). All of the above supports that extensibility is currently considered a desirable characteristics of current design environments (91; 247), and is even among the requirements specified when developing certain packages (41; 91). Some of the main ways in which this characteristic is being enhanced in the present day will be explored below.

Many of the approaches related to previously analysed trends in this review also serve as great aid to improve extensibility aspects. For instance, common data models have been noted to enhance extensibility, as the data format can remain constant even when changing or adding new tools to the suite (41; 95). The extensibility of data models themselves constitutes another topic which shall be expounded further below in this subsection. Some of the approaches to improve system extensibility are based on maintaining common interfaces for different types of analyses and employing object-oriented programming (247), which are also related to KBE approaches as developed beforehand.

Modularity is also a key enabler for environment extensibility (91), as it can enable to integrate new models of existing disciplines, add novel disciplines overall, and even modify the order of the analyses through a reorganisation of the workflow, as seen in 4.4.2. The design of different aircraft types does not only require a distinct knowledge, but also different tools and methods that are applicable to these novel aeroplanes, which links with extensibility concerns. As mentioned beforehand within subsection 4.4.2, unconventional layouts may require specialised methods within discipline analyses, such as novel mass estimation approaches for BWB configurations (59), or a new performance module for hybrid-electric aircraft (91), with these novel layouts sometimes even necessitating reorganising the overall workflow. Thereby, with added tool extensibility, the framework can adapt to the needs of these novel aircraft concepts while maintaining the same baseline architecture. This would allow to incorporate specific modules for aircraft for which common and well-established analyses are not applicable, and to select these alternative procedures when developing an aeroplane with these characteristics (59). Connecting with the topics of data formats and interoperability, the addition of new modules can be further enabled if a central node which manages the inputs and outputs of the novel modules in a central data format is employed. Overall, it can be seen that both the architecture of the system and the data exchange format are fundamental for added design environment extensibility.

Following with interoperability and integration aspects, these can also be considered to improve extensibility, as it is easier to connect new modules with the existing ones. Furthermore, interoperability with external software can also aid in the matter of expanding current environment capabilities, as these programs can enable to cover aspects which were not within the core features of the package, as commented in 4.4.2. This line of work also presents its hurdles, for which some ways of tackling them, such as wrappers or common data formats, were already expounded beforehand.

The notion of extensibility can also be applied to the common data format employed in the environment, and it can also constitute a relevant topic, as the capabilities of the package might not only require expansion in terms of methods and tools, but also in the data format itself which is used to describe the aircraft concept that evolves through the design continuum. This can be the case when extending the design environment to cover more disciplines, more phases of the design continuum, or even aeroplane types with special characteristics, such as RPA with their particular payloads, equipment, and missions. Extensibility of data models has been emphasised particularly when dealing with different tools, tasks, and levels of fidelity. This property is emphasised in data formats such as ADDAM (41) and the data model employed within the CREATE-AV Aircraft Design, Analysis, Performance and Tradespace (ADAPT) tool (242). The extensibility of these type of data formats is enhanced due to properties of their models such as class inheritance, which can enable that subclasses inherit the properties of super-classes. For instance, if the property MTOM is defined for an aircraft, and an aeroplane is a subclass of aircraft, then aeroplane inherits the MTOM property. This notion can also be

leveraged in OO paradigms, as it has been applied in the SUAVE aeroplane design environment (247).

The particular case of extensibility within the KEACDE framework should also be highlighted. This paradigm does not only emphasise data model extensibility, but also scalability of the tool repository included in the suite. These tools are made available as knowledge components and their interoperability is ensured through wrappers, as developed beforehand. Through this KBE-based approach, the framework even enables to develop novel design environments themselves, each with their particular application scope, from the basic scalable suit serving as the base layer (95). The notion of a scalable tool repository employing wrappers is also put into practice in the ADEBO environment (41).

Current methodologies: use of approaches emphasising modularity and interoperability, common data formats, object-oriented programming.

4.4.5. Method flexibility and multi-fidelity capabilities

As introduced in subsection 2.1.2, there is a remarkable variety of disciplines involved in the design process. Many of them admit different modelisations of the type of problem of phenonema on which they are focused. These distinct models can present varying applicability scopes depending on various considerations. For instance, a weight estimation model can be expected to vary depending on the aircraft type (ultralight, normal category, transport category, military, etc.) (8; 11), and a performance model can require different integrations of the range or endurance equations depending on the flight law and profile (9). These variations between models can also be present in terms of varying fidelity, such as aerodynamic methodologies which range from semi-empirical approaches, to vortex-lattice numerical methods, on to complex CFD calculations (250). Depending on the design case scope and stage, the most suitable approach is expected to differ.

Considering, the availability of an array of possible methods to be used within the workflow of a computerised environment constitutes a significant aid for the designer. As a matter of fact, improved flexibility in method selection is among the main current trends within this field, which even serves as enabler for further capabilities, such as the design of unconventional aircraft and RPA (17; 55; 91), as it will be discussed below and in the following subsections. This kind of approach was already outlined in previous subsections, such as when commenting the possibility of swapping the methodologies present in some of the building blocks of the design workflow to adapt the design process to unconventional configurations (59). This method flexibility can be considered both at a general level, and from a fidelity-centred perspective, the latter of which is aligned with the “multi-fidelity” concept seen through the state-of-the-art. Both of these approaches shall be expounded first, and then the current approaches, situation, and possibilities of these capabilities will be expounded.

(a) Overall method flexibility

As mentioned beforehand, a single discipline can cover a wide range of possible methods depending on various aspects: fidelity, applicability scope, analytical or numerical approach, etc. The dimension covering method flexibility based on various possible fidelity levels shall be covered in detail on the following point, while here other aspects shall be emphasised.

The scope of design methodologies is one of their main fundamental characteristics as discussed in section 2.1, as it restricts their application range. This can include, for example, the statistical weight estimation through different regressions depending on aircraft type, or the distinct modelisation of the integral performance flight mechanics equations depending on the kind of mission, as commented beforehand. If different variations of a particular discipline model are available, this usually results in an expansion of the applicability and thus usability of the design environment. As it will be seen in section 4.5, within the realm of manned aeroplanes, some environments are capable of sizing aircraft of various types, with one of the enabling characteristics for this being the implementation of different design approaches within the software suite. Therefore, an increase in method flexibility can be considered as a desirable characteristic of the design package. Other possible variations among methods which can be implemented can include the availability of both analytical and numerical approaches, as each of them has its own set of advantages (250; 251); and even dissimilar approaches as obtained by different authors, which is a common occurrence in the field of statistical estimations, where variations for the same aircraft type can be seen among distinct references (7; 8; 9; 11; 48), since the results depend on the database employed to obtain these expressions.

(b) Multi-fidelity capabilities

The concept of model fidelity was introduced in subsection 2.1.2 along with its strong couplings with the required computational resources and the different stages of the design continuum where each kind of approach can be leveraged to a greater extent. The concept of “multi-fidelity” capabilities has been described in the field of aircraft computerised environments as the method and tool flexibility enabling to employ approaches with varying fidelity levels at different points of the design continuum, allowing the designer to use the adequate level of fidelity at the proper time to achieve the desired level of accuracy with an acceptable computational cost (17; 85; 91). Within the context of this thesis, this concept can be considered as a particular case of the more generic one of “method flexibility” expounded above, focusing here on the characteristic of fidelity level.

One of the foremost advantages provided by multi-fidelity method flexibility is that, attending to the relationship between the fidelity level and the design phases and the progressive refinement concept as introduced in subsection 2.1.2, it can enable the design

environment to cover in its scope various stages of the design continuum. Thus, lower fidelity methods can be used at the first stages to rapidly explore a large design space, and then once the preliminary phase starts, medium or high-fidelity approaches can be employed to refine the initial predictions (17; 51). As mentioned beforehand in this thesis, this fidelity sequencing schema is still being considered in recent research works and design processes (51; 69; 74; 75).

The fact that the design environment can cover various stages in the development process, thus covering a wider spectrum of activities of the design continuum, has been noted as a desirable characteristic in previous works, since it allows the same digital model of the aeroplane to be developed and evolved through the different phases of the design process while maintaining the “digital thread” of the concept, which represents the development process of the asset that will ultimately be manufactured (100; 245). This “digital aeroplane” evolves at every step of the design, since more data about the model is known as the design procedure continues, allowing to switch to higher fidelity analyses, thus achieving more detailed results. These results, in turn, permit to define the model at a more detailed level, allowing to apply more accurate analyses and so on, all within the same design package. This method flexibility allows the designer to balance run time with the required accuracy at each step (17). Additionally, when the environment covers various design phases, it allows the transition from one to the other to be smoother (100), both in terms of data and workflow.

To enable this capability and to achieve a comprehensive program that can be used in different stages of the design process, it is required that methodologies pertaining to different fidelity levels are implemented in the design package so as to allow the user to choose amongst them at the most adequate time within the design workflow (51; 86). Firstly, the methodologies to be integrated within the environment must be selected, which is a process usually done by classifying the methods by discipline and level of fidelity. Classifications according to these criteria having been developed in previous works such as (63; 71; 232; 252), among others. These have been used to plan the coding tasks towards enabling multi-fidelity approaches within design environments.

There are other notions related to the multi-fidelity concept which have been found in the open-literature. One of these emphasises the possibility of the overall timeline of the design process being expedited through greater efficiency, which can be enabled by the design environments themselves, as it was already commented in the introduction that this is one of their main purposes. This would allow within the design timeline to accelerate the beginning of the tasks related to the preliminary and detailed design phases, and as a consequence this would bring forth the use of higher fidelity approaches to an earlier point in time. This idea of shortening the lead time to further design stages have been among the main objectives of previous research in computerised environments (70; 92).

(c) Current trends and considerations

In order to enable the flexibility of methods within the design environment, it is required to select and implement the methodologies themselves within the software suite. To allow this, it is first required that the methodologies exist, having been formulated at a conceptual level, so that they can then be implemented. Albeit this is mostly the case for methods of various characteristics in the case of traditional aircraft, it was seen beforehand in chapter 2 that certain areas of RPA design approaches present remarkable gaps, thus difficulting the implementation of specific methodologies for these aircraft in computerised environments. This is a similar situation to that of the area of manned aircraft unconventional layouts, where there is currently a significant effort in the development of new design approaches (58; 60; 219). Thereby, an initial effort would firstly be required in the development of these approaches at a conceptual level, so they can then be implemented in design environments. Novel design methods at the different fidelity levels for these unconventional aircraft types would be required so that a true multi-fidelity capability can be enabled, thus allowing the development of software suites which can cover the different stages of design for these kinds of aircraft. At the same time, once the design methodologies for these unconventional concepts have been integrated within the environment, its applicability range and method flexibility are greatly enhanced, since it can now also perform the sizing tasks for these aircraft types by modifying the workflow to use the methods required in each case. Further aspects related to the current scenario in unconventional aircraft and RPA design methods and their implementation in design packages shall be commented in the following subsections.

However, aside from the availability of design methods at different levels of fidelity and with distinct applicability ranges, their implementation within the design package also needs to be addressed so that the desired flexibility capabilities are achieved. This process of integrating the new methodologies in the design package is tightly linked with the trends evaluated within the previous subsections, as they are mainly related to software architecture and computational workflow aspects, which must also be considered when integrating the aforementioned design approaches in the software suite. These connections of the different previous trends with flexibility considerations were already developed beforehand in the corresponding subsections. For instance, it was seen in subsection 4.4.2 that modularity enhanced the capability of changing or adding building blocks to the design workflow, with the particular examples of **¡Error! No se encuentra el origen de la referencia.** showcasing the ways in which new methods for unconventional configurations could be integrated. Some specific comments which are more focused on the topic of flexibility are given below.

Often, higher fidelity analyses are not implemented as internal modules of the software. Rather, they are conducted through external software which is linked to the design workflow of the core environment. This is the approach that has been employed, for instance, in the SUAVE design environment (85). In this way, the design package does not

require to implement such complex simulations as part of its core capabilities, which would be very costly, and instead it leverages existing specialised software tools which have already been extensively tested. This is a way to enhance environment flexibility and multi-fidelity without a need to modify its core architecture. However, in this case interface and integration aspects have to be considered, which can be addressed through common data formats or wrappers, as commented through the previous subsections. For instance, the CPACS data format has been employed for data exchange to enable multi-fidelity capabilities through the connection of design packages with external software (253). Furthermore, it was mentioned that CPACS, ADML, and ADDAM are all compatible with aircraft definitions both at the conceptual and preliminary design levels. Thus, these data formats would also aid in establishing comprehensive design programs covering various design phases, as mentioned beforehand.

It can be seen that there is a tight connection between flexibility and multi-fidelity capabilities with the previously analysed trends. Thus, design environments which are focused on these aspects have also paid close attention to the previous dimensions. This is the case of ADEBO, where modularity and integration aspects were emphasised so as to enable multi-fidelity capabilities (41; 254). Other recent environments showcasing multi-fidelity design options include SUAVE (55; 85), LEAPS (91), and the RPA design package developed in the work of (17).

Finally, it should be highlighted that this trend presents remarkable connections to both main areas of interest which were commented in the introduction. The first one is related to design methodology capabilities, and it related to the current trend since the purpose is to expand the applicability range of the design environment through flexibility in its implemented methods. At the same time, the second area, related to software architecture and workflow management, is also key, as it enables the implementation of the design methodologies themselves within the suite. This can be seen through the relationships of the current trend with the ones discussed beforehand, which were mainly related to this second area, as commented in their corresponding subsections.

Current methodologies: development of new design methodologies with varying applicability and fidelity levels, enabling the implementation of the aforementioned methods through modularity and interoperability aspects, use of external software.

4.4.6. Unconventional configurations

As mentioned in the introduction to this chapter, the study of unconventional aircraft configurations is a field that is attracting noteworthy interest not only within computerised design environments, but also in the broader realm of aircraft design itself. The investigation of these types of layouts has experienced an increase from the decade of the eighties onward, motivated by the diverse petroleum crises as well as the rising environmental and economic pressures in the aviation industry (255). This has resulted in an increase of research studying the potential efficiency benefits that could be achieved

through aircraft concepts which deviate from the usual conventional configurations, which consist in a tube fuselage, a wing, engines under the wing or attached to the rear-end of the fuselage, and a tail configuration consisting of a horizontal and a vertical surface either in a conventional or T layout. This configuration is only achieving incremental improvements in efficiency in the past years, not accounting for the improvements in fuel consumption due to updates in engine technology and design (12).

Meanwhile, the demands for improvements in aviation efficiency and fuel consumption are increasing. The Advisory Council for Aviation Research and Innovation in Europe (ACARE) has set goals of a 75 % reduction in CO₂ emissions per passenger-kilometre, a 90% reduction in NO_x emissions, and a noise reduction of 65 %, all of them for the year 2050 and measured with respect to aircraft of the year 2000 (220). It is expected that it will not be possible to meet such demands just through small, incremental improvements on the conventional layout (91). Rather, revolutionary changes will be required, which is the main reason behind the remarkable volume of research in analysing the possible benefits that can be achieved in these areas by modifying the general layout of the lifting surfaces in aircraft so as to evaluate whether unconventional layouts can be the key to achieve the aforementioned demanding goals (12; 51; 91). To this end, it is first required to adapt existing methods or to develop new ones for the analysis and design of these aircraft.

Most of the types of unconventional aeroplane configurations which are currently being studied can be substantiated through an analysis of the expression of the drag coefficient C_D considering a simplified parabolic aircraft polar, which serves as basis to identify different options to reduce drag:

$$C_D = C_{D0} + \frac{C_L^2}{\pi AR_w \varphi} \quad [4-3]$$

Where C_{D0} represents the non-lift dependent drag coefficient, C_L represents the aeroplane lift coefficient, AR_w is the wing aspect ratio, and φ constitutes the aeroplane efficiency factor (51).

The main strategies for drag reduction that can be identified from the previous expression give birth to diverse types of unconventional layouts:

- 1) **Reducing C_{D0} :** this strategy implies reducing the wet surface of the aeroplane, thus giving place to BWB and tailless configurations. These are among the unconventional layouts which have been studied to a greater extent (51), with new analysis approaches having been developed for their evaluation (256), and previous design works showing promising results (257). When compared with conventional configurations, they have been noted to present higher aerodynamic efficiency, leading to lower fuel burn, emissions, and noise, as well as lower operational cost overall (60). Some of these layouts have been analysed with

state-of-the-art computerized design environments (59; 85), resulting in reductions of MTOW of up to 10.9% in comparison to conventional configurations with similar initial requirements (59).

- 2) **Increasing AR_w :** this way gives birth to very-large wing aeroplanes, which usually necessitate to alleviate the wing internal forces and moments near the root through the use of truss unions to the fuselage (51).
- 3) **Increasing φ :** increasing the aerodynamic efficiency factor mainly involves reducing the intensity of the wing tip vortexes, thus vortex-induced drag. This can be achieved through various means: winglets, wing fences, raked wings, and non-planar wing configurations such as the joined-wing and the box-wing (258). Previous studies have proposed and analysed these latter concepts, achieving promising results (58; 259; 258; 260). For instance, in a previous study, it was seen that nonplanar configurations have the potential to achieve better performances than conventional aircraft, with the joined wing configuration achieving 17% increases in range with an improved efficiency (58).

Figure 4-7 illustrates two examples of unconventional aircraft configurations mentioned above. Other concepts include layouts such as C-wing aircraft, tandem wing, canard configurations, and tri-surface layouts, among many others, with these layouts also attracting research to evaluate their particular characteristics and feasibility. For instance, the study of (261) analysed the interference effects of adding a canard lifting surface as a layout modification. It must be noted that these unconventional configurations can also be focused on the tail surfaces, such as in the case of modifying the conventional tail of a commercial transport aircraft to a V-tail empennage (43; 262).

Studies in this field tend to perform trade-off studies to assess the comparative advantages of the novel layout with respect to a baseline aircraft, with both concepts being designed with equal initial specifications so that they are comparable (43; 51; 58; 60; 257). This allows to evaluate whether the investment on the new configuration results in significant advantages which can substantiate the effort of designing such an aircraft type instead of a traditional one. This kind of study requires additional care when setting up the methodologies, which must either be flexible enough to cover various types of layouts at the same time, or rather if the methods have different applicability ranges they still have similar procedures and underlying hypothesis, so as to ensure that their results are comparable.



Figure 4-7: examples of revolutionary unconventional aeroplane configurations. (a) Left-hand-side image: box wing configuration example from Lockheed Martin (image from commons.wikimedia.org). (b) Right-hand-side image: BWB configuration from Boeing-NASA (image from commons.wikimedia.org).

In spite of the interest in this field due to the promising prospects of these configurations, it should be highlighted that the designer faces significant hurdles when addressing the development and application of methodologies for their design and analysis. Many features of these aircraft are far apart from the traditional ranges of values seen in conventional aircraft (91), and their layouts are also significantly different to the usual ones, leading to distinct hypotheses when addressing their analysis. Thereby, and as commented in chapters 1 and 2, the applicability of proven approaches, both empirical and also those based on physical modelisations, can be debatable. This requires a substantial effort in the development of new analysis and design methodologies, as seen in the previously cited references. The recent survey of (219) provides an overview of different unconventional layouts along with current analysis approaches for each of them.

Having seen some background aspects related to the study of unconventional configurations in the broader realm of aircraft design, the particularities of their consideration within computerised environments shall now be expounded.

Previous works have highlighted that there is still room for improvement within the current frame of computerised environments regarding the available approaches for unconventional layout analysis and sizing (91; 92; 93). This links with the first of the two main limitations in current design packages as seen in the introduction, which stated that present-day methodologies are usually focused on a single type of vehicle, in this case the conventional layout (17). As seen beforehand, novel configurations require new methods of analysis and synthesis, so they represent a challenge to legacy design packages, which might not offer reliable predictions for novel aircraft concepts, thus requiring the development of new environments or the thorough update of previous ones to include the required methods and capabilities to address the design of these layouts (59; 91). Aside from the challenge of developing new methodologies themselves so that they can be implemented in the design packages, from the viewpoint of the design environment itself, further hurdles appear due to the additional intricacy of the design process, which may

require a tighter coupling among analysis disciplines, a more extended use of higher fidelity approaches, and a framework to allow configuration comparison through trade studies (91). Therefore, it can be seen that the development of design packages for the study of unconventional configurations is not a straightforward matter.

At the same time, and as outlined in the introduction to this chapter, due to the overall advantages that computerised environments represent, and so long as the above-mentioned hurdles are tackled, it is considered that these packages represent a promising prospect for the design and analysis of these types of vehicles. This is due to their capabilities to perform coupled analyses in efficient frameworks, their potential extensibility and flexibility to adapt their methodologies and workflows, and the higher level of fidelity which can be leveraged for example through the interface with specialised external software. Thereby, if the current challenges towards adapting these software suites for their use in unconventional configuration analysis and design are surmounted, they are expected to constitute effective and efficient tools which can aid and expedite the design of these aircraft types. As a matter of fact, the research in many of the trends which have been previously analysed in this section has been motivated in part because they have been identified as key enablers towards adapting current frameworks for the design of unconventional layouts (41; 55; 59; 91; 93). Some of the connections between the areas of work corresponding to the previous subsections with that of unconventional configurations have already been outlined beforehand, with some further comments provided below.

In order to adapt current environments to the design of unconventional configurations, or to create novel packages specifically tailored to these particular aircraft, the first step is that the analysis and design methodologies themselves must exist at a conceptual level, which is required so that they can then be implemented in the design software (93). This is an issue linked to the first of the two main areas of interest in design environments as mentioned in the introduction, which is related to the design capabilities of the methods themselves. Thereby, a noteworthy research effort in the overall area of aircraft design would first be required to develop such methodologies. As it has been seen above, there are remarkable current efforts in this line of work which have already yielded design procedures for these aircraft with promising results (58; 60; 257; 219), albeit there is still room for improvement since methods for different design stages and disciplines have yet to be developed (59; 219).

The capabilities of computerized design environments regarding the design of these kinds of configurations are highly dependent on the implementation of specific procedures which are tailored for their sizing and optimisation, as well as physics-based high-fidelity methodologies (59; 91; 247). The introduction of higher fidelity approaches is clearly required in order to achieve accurate results for unconventional aircraft concepts at later design stages. However, as expounded in subsection 2.1.2, other kinds of methodologies would also be required for the earlier phases, where a large design space must be

explored while controlling the computational effort required. Therefore, the development of novel rapid analysis and design approaches for these unconventional aircraft would constitute a remarkable asset to cover this area. As a matter of fact, the investigation on conceptual design methods for these aircraft is not only a key area of research among the references within the overall realm of aircraft design (58; 60; 259), as also the integration of these rapid approaches in design environments is being actively sought after (59; 70). Overall, the availability of both low and high-fidelity methods is considered key for the design of unconventional layouts within the context of these software suites (93). Furthermore, if both lower and higher fidelity approaches for unconventional layouts are at hand, this could also enable to develop comprehensive multi-fidelity design programs that cover various design stages for these aeroplanes, as highlighted in the previous subsection.

Once design methodologies for unconventional aeroplanes are available, their implementation in the computerised environments also requires particular considerations which are tightly linked to many of the previous trends analysed in this section. Regarding KBE based approaches, it has been highlighted that different types of aircraft demand distinct design knowledge and methods, thus a more intensive deployment of KBE methods can aid to adapt design environments to the development of these layouts (51). With respect to modularity and method flexibility, these are desirable characteristics to enable the integration of unconventional vehicle analysis and design approaches in the workflow. This was seen for the GENUS and AGILE design environments in subsection 4.4.2 and **¡Error! No se encuentra el origen de la referencia.**, where both the swapping of design methods within a specific module, as well as their rearrangement in the workflow, were seen as ways to adapt the design approach to these layouts. The integration of the new methods themselves would also benefit from the consideration of flexibility and extensibility aspects, which would aid to seamlessly implement these new additions, expanding the capabilities of the environment itself (17). All of these aspects would be key to conduct trade studies within the same design package, which is one of the foremost objectives for environments seeking to address unconventional layout design (17; 59; 92).

Interoperability also plays a large part in the integration of novel design methods for unconventional layouts within the environment. This does not only apply to the seamless connection of the new methods and modules with the others (91), but also to the extended employment of external software to perform high-fidelity calculations. As mentioned above, the use of physics-based high-fidelity methods is one of the main lines which has been investigated to enable unconventional vehicle design in computerised environments (55; 155). This also fits within some of the possible approaches to enable multi-fidelity capabilities as commented in the previous subsection, in this case through leveraging external software to complement the core capabilities of the system, thus also linking with extensibility aspects. In view of the connections of the trend of unconventional aircraft design with the others, the approaches which have been commented in the previous

subsections would also be useful to aid in the implementation of the present one. This includes the employment of common data formats, of which ADML as mentioned beforehand has been developed specifically to tackle unconventional vehicle concept representation (240).

Therefore, even though the development of design methods themselves to size unconventional aircraft is tightly related to the first main area of interest as commented in the introduction, their implementation is also dependent on advancements on previously commented trends, which are more related to the second area of interest, that of software architecture and workflow. Overall, as it can be seen, to reach the objective of developing a design environment aligned with the design of unconventional aircraft, it is required to advance in parallel both in the area of developing new design methodologies for these aircraft, as well as in that of the implementation of such approaches within the suite. This latter point is expected to require the application of many of the aforementioned trends such as KBE, flexibility and extensibility, with advances in their areas acting as enablers to reach the purpose of unconventional vehicle development within computerised design environments.

Current methodologies: development of specific methodologies for unconventional configurations, high-fidelity physics-based calculations, improvements in implementation aspects related to previous trends and challenges.

4.4.7. Remotely Piloted Aircraft Systems (RPAS)

In recent times, there is an increasing interest in the expansion of the design capabilities of current environments so that they can cover the design of RPAS, and also in the development of new specialised design environments for these aircraft. This can be seen in novel packages which have been tailored for their use in RPAS design, such as CCADE (70) and RAMP (61), and also in other environments that cover the design of various types of manned aircraft and which are also supplemented with capabilities in terms of RPAS design, such as SUAVE (93), GENUS (59), or AGILE (133; 155).

Most of the considerations for the integration of RPAS design capabilities within design environments follow a similar rationale than those for unconventional layouts as expounded in the previous subsection, with some added peculiarities. Since this aircraft type constitutes the main topical area of this thesis, the text has already covered various aspects which would apply to the current subsection, including the main challenges towards developing new design methods for RPA, the current gaps in this regard, a coarse overview on the present status of computerised environments for RPAS, and how the gaps of different topical areas in design affect others. Thereby, a summary is provided here of the main points already developed beforehand in this text and how they link with the challenges of integrating RPA sizing aspects within aircraft design environments:

- In a similar manner to unconventional layouts, and as discussed in section 1.3, the particularities of RPA and their differences with manned aircraft demand a thorough adaptation of current design approaches or a development of novel ones tailored for these aircraft. Furthermore, configurations which are usually labelled as unconventional for manned transport aircraft are instead commonplace in RPA, with V-tail, H-tail, and tailless layouts being some examples (6; 35), so the applicability concerns regarding existing methods which were mentioned in the previous subsection would also apply here.
- As an additional consideration for RPA, they also present a high diversity of powerplant options. Whereas works on manned aircraft unconventional layouts are primarily focused on turbine engines, RPAS are mainly equipped with internal combustion engines or electric motors (36; 39). Thus, their powerplants are radically different to those types of engines which are more typical within current design software, therefore also requiring specific methods in this area (156).
- In the same way as it was said above for unconventional configuration, the first step towards enhancing current environments to add to them the capability of designing RPAS is that design methodologies for RPA must exist at a conceptual level, which is necessary for their subsequent implementation in design software.
 - An evaluation of the current status of RPA design methods was provided in chapter 2, and it was seen that there is still room for improvement in many of the topical areas which were analysed. In view of this, and as already anticipated in that chapter, the availability of new design methods for RPA would constitute a prerequisite for their implementation in design environments.
 - The way in which different topical areas of RPA connect and depend on one another, as seen in Figure 2-4 and discussed in the review of chapter 2, set up an scenario where the development of methods in some of them would be needed to serve as foundation for those of other topical areas. It can be considered that the current gap in RPA computerised environments is in part due to this aspect.
- Once the design methods for RPA are available, their implementation on computerised environments would follow the same considerations as in the previous subsection on unconventional configurations on aspects such as KBE, modularity, interoperability, and extensibility, with all of these characteristics serving as enablers for the integration of RPA design capabilities in design packages.
- Flexibility and modularity considerations would be key towards enabling trade studies (21; 33), which are particularly relevant taking into account the variety of

layouts that RPA designs showcase (6), but also the fact that in most cases there does not seem to be a single configuration which is the most prevalent (38). This shall be analysed in detail within chapter 7, where novel statistical results pertaining to the trends in configurations shall be obtained.

- An additional consideration of RPA is their multi-mission nature, which has been considered to be one of the main reasons for the design diversity of these aircraft (1; 21). Most previous studies of unconventional configurations have focused on commercial air transport missions. An additional hurdle faced in RPA design is in their mission variety, as discussed in section 1.3. Thereby, both the design methods and the computerised environment itself would require to consider a larger flexibility in mission definition profile, variables, and in flight law, so as to provide procedures to model and represent this mission diversity. For instance, the most prevalent mission for RPA is ISR (26), which can present flight profiles and performance parameters that are notably dissimilar to the usual missions of transport aircraft.

Previous authors who have developed their own RPA design environments have also emphasised some of the previous points, highlighting that the fundamental differences of these aircraft with traditional manned ones require the modelisation of dissimilar operational scenarios and the development of new sizing algorithms and tools (17). Therefore, the capabilities of design software for their application on RPAS depends largely on the specific methodologies which have been implemented in the design package, so once again, the flexibility and extensibility of the design packages becomes a relevant asset for establishing new methodologies to design atypical aircraft.

Regarding the current state of computerised environments for RPA design, albeit currently few design packages have been developed, some examples of the ones found when conducted this survey have been mentioned at the beginning of the subsection. As commented beforehand, RPA design environments can greatly benefit from advances in the previous trends analysed here, with many cases being similar to those discussed in the subsection on unconventional configurations. As an example, with respect to common data formats, two of the most extended ones include capabilities which can be valuable for RPAS design. ADDAM has been demonstrated the capability of providing geometric representations similar to existing RPA concepts (41). Furthermore, as commented in the previous subsection, ADML is particularly focused on unconventional layout modelling (240).

In section 4.5, which addresses the evaluation of the key features of current computerised environments, more specific insights shall be offered on the current status and the capabilities of RPA design packages, thus completing at a more detailed level the overview on this area already provided within chapter 2.

Current methodologies: development of specific methodologies for the design of RPAS and unconventional configurations, improvements in implementation aspects related to previous trends and challenges.

4.5. Analysis of key features of computerised design environments

In the previous section, a review was conducted of the topics representing the foremost areas of research in recent times within the area of fixed-wing aircraft computerised environments. The focus was on the main trends and challenges which are common across diverse design environments. Furthermore, the main methodologies that have been applied in present-day packages to address these areas of work were also discussed.

The former survey did not only seek to cover the first objective of this chapter, but it has also laid the foundation for the analysis to be developed within the current section, which is related to the second objective. As outlined in the introduction, the goal here is to perform an assessment of the characteristics of existing computerised design environments, so as to capture an image of the current capabilities of design frameworks, and to see to what extent they can cover the challenges studied beforehand. Thereby, the viewpoint shifts from an overall analysis of areas of interest present through different design packages, to a study of the number of existing packages that showcase certain key features related to those areas.

In order to accomplish the objective of this section, it is first required to define a set of features which are associated to the main trends and challenges in this field. The review conducted in the previous section proves crucial in this regard, as various couplings among the different trends have been detected, and the analysis of current techniques in each of the areas allows to extract a series of desirable characteristics which are related to improvements and capabilities in relation to each of the aforementioned lines of work. These features associated to the trends analysed beforehand shall be complemented with others to provide an overall description of the scope and capabilities of current design frameworks. Once the set of key features has been established, and following the review process considerations previously commented in section 4.3, a number of representative design environments found in the state-of-the-art analysis shall be evaluated, quantifying how many design environments present the aforementioned features.

The analysis conducted here will allow to assess the current scenario of computerised design environments in terms of overall characteristics, revealing which areas might require future work, particularly in relation to the main challenges developed within the previous section. Moreover, these results will also link with the third objective of this chapter, which seeks to assess the situation of the current landscape of computerised environments in terms of addressing the main design challenges of RPA, which as seen

beforehand, is one of the main lines of work identified in the previous section. This point shall be developed in the following section in view of the findings of the current one.

The process of identifying the key features to be evaluated in this line of work shall be developed within 4.5.1, not only including those connected to the review of the previous section, but also others related to the scope of the implemented design processes, general capabilities of the software, etc. Then, in subsection 4.5.2, the prevalence of each of these features within this domain shall be analysed, with the results allowing to assess to what extent the existing packages cover the trends and challenges identified beforehand, and which areas might constitute avenues of future work. In view of the findings from this analysis, subsection 4.5.3 provides a summary of the main conclusions regarding the current state of this field in relation to the trends and challenges of section 4.4.

4.5.1. Identification of key features in aeroplane computerised design environments

As mentioned above, to perform the capability assessment of state-of-the-art design environments, it is first required to identify a set of relevant characteristics to be used in the analysis. The definition of a common set of features to evaluate current design environments is not a straightforward matter, as noticeable heterogeneities can be found within the current frame of design packages (63). In the case of this research, as mentioned beforehand, these features shall be related to the main trends and challenges identified through many different environments in the survey of section 4.4, as well as to other features which provide an overview of the main scope and capabilities of the environments. This subsection covers the process of definition of this set of key characteristics.

In order to define a set of potential features of design environments related with improvements and capabilities pertaining to the key trends and challenges within this field, it is first required to analyse these areas themselves, paying close attention to two types of aspects:

- 1) The connections and dependencies among the different trends and challenges themselves. That is, the way in which addressing some of them can aid to tackle the main hurdles of other ones.
- 2) The approaches, methods, and techniques that can be implemented in the software, and which are related to its performance in relation to the challenges that are being considered.

Taking into account these two aspects in combination is essential not only to identify the features associated to each of the seven lines of work identified in the previous section, but also to relate these features to the challenges which they help to address. For example, it was commented in section 4.4.1 that the development of a central data model served as

a valuable asset towards improving KBE-related capabilities, since it provides a common formal representation of the aircraft concept which is being developed. At the same time, it was seen through 4.4.1 and 4.4.2 that interoperability could be enhanced by KBE approaches, including among other possibilities the use of a common data format as a central node for module connection and interfacing. Thereby, it can be seen that, due to the dependencies between the trend of interoperability with that of KBE methods, the use of central data models -which in their origin would be related to the area of KBE- can benefit advancements in both trends. Similarly, improving environment modularity aids in method flexibility, as a modular organisation of the environment allows for discipline models to be swapped within the same design loop to account for different possible sizing approaches or analysis considerations. Thereby, design package features which aid in addressing a certain challenge can also benefit the process of tackling other hurdles which are downstream in the dependency flow among these areas. This is similar to the connections among the topical areas analysed in chapter 2, which resulted in some of them serving as key enablers to cover the gaps in others.

The connections among the different trends, as well as the main approaches that are being currently employed associated to these areas of interest, have both been expounded through the previous review. Even though it was seen that there is still room for improvement in some of these areas, some approaches which have already been implemented in existing environments have shown promising results in surmounting the main hurdles related to these trends. Thus, these current approaches have been employed to define features which improve the software performance in relation to each of the trends and challenges, also accounting for their dependencies. Even though other ways of tackling the main hurdles related to each area may be found, the current ones can serve to provide a measure of the capabilities of design environments in these areas. In any case, further on in chapter 5, it will be seen how other novel approaches can benefit some of these lines of work.

Considering the above, Figure 4-8 illustrates the main relationships between the different analysed trends, as well as the key features defined in this section for the evaluation of the capabilities of computerised environments in relation to each of them. This figure also serves as a summary of the main aspects of the review of section 4.4 which are also linked with the present one, albeit it is noted that the network of conceptual interconnections is remarkably complex, as seen through the development of the previous section, so this figure is focused on the main links and dependencies. The identification of the relationships among the trends, as well as the definition of the capabilities related to each of them, can be considered among the main results derived from the analysis work conducted in relation to this topic of the thesis.

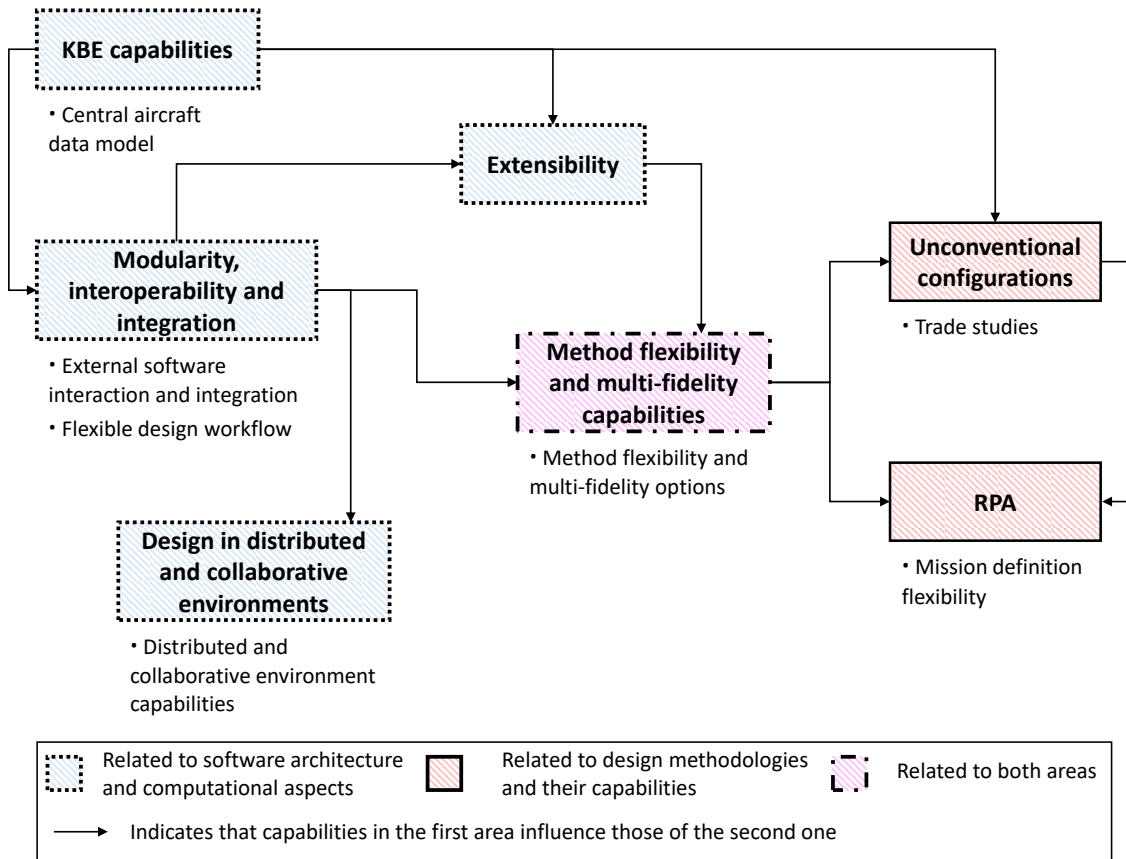


Figure 4-8. Relationships among the different trends analysed in section 4.4, represented by the boxes, along with the selected features which are related to the design environment performance for each of them, represented by the text below the boxes. Each trend has been associated to the two main areas of interest in the overall realm of computerised environments as laid out in section 4.1.

The connections and dependencies among the different trends illustrated in Figure 4-8 have been expounded in detail through section 4.4, where the relationship of each of the trends with the two main areas of interest have also been discussed. The features which have been proposed in relation to each of the trends represent some of the main current approaches in each of these areas, as also commented in the previous section. While some of these features are already relatively extended, others are yet to be implemented and leveraged to a further extent, as it will be seen in the following subsection. As mentioned above, features associated to a certain trend are not only beneficial in their own areas, but also downstream regarding other challenges which depend on the precedent ones. As an example, central data models such as CPACS or ADML, which would be related to the trend of KBE capabilities, have also been developed towards enhancing design in collaborative environments, thus aiding to this trend, which is downstream to that of KBE as seen in the figure. Therefore, those features that are upstream in the chain of dependencies among the trends as showcased by the arrows of Figure 4-8 have the potential to benefit various areas with their implementation. This is also the reason for the extensibility trend having no explicit associated feature, as it is already aided from central data models, the

capability of interacting with external software, and a flexible design workflow, which are all associated to trends upstream from this one.

Another key takeaway from the figure is that, while the trends of unconventional vehicle and RPA design are mostly related to the first main area of interest laid out in 4.1, they are dependent on advancements on trends and challenges which are more strongly related to the first area of interest. As commented in 4.4.6, the purpose of developing design packages for unconventional configurations and for RPA are amongst the most noteworthy purposes of the current landscape of computerised environment research. However, as these aspects are strongly benefitted from advancements required to surmount other challenges, they are also serving as drivers for the investigation in other trends such as modularity, interoperability, and extensibility. This can be considered to explain why it has been recently that aspects and features related to the second area of interest, that which is more related to software engineering and design workflow, have seen an uprise in recent times, since they do not only provide advantages in their own fields, but are also key towards reaching the objective of developing design packages for unconventional layouts and RPA. This establishes a strong relationship between the two main areas of interest, as advancements in the first one depend on those of the second. Thus, it can be considered that features related to both of these areas are fundamental in enhancing future design environments. This substantiates the notion introduced in 4.1 that computational aspects have a relevant impact on the implementation and deployment of design methods, which is also the reason for taking both aspects into account in the context of this thesis.

In view of the above, the set of characteristics which will be evaluated in the computerised environment assessment to be conducted within this section can be defined. As mentioned beforehand, these features shall consider aspects allowing to describe the current state-of-the-art of these environments, including both those which are more descriptive of the general scope of the design packages, as well as those related to the aforementioned trends and challenges. Reviewing the number of existing environments which present these different characteristics will not only deliver a description on their present capabilities, but it will also provide a measure on the capacity of currently available design packages to address the main areas and interest and challenges of this field. A list of the different areas analysed are shown below:

- 1) **Phases of the design project covered:** using the definitions of the design continuum classification as laid out in subsection 2.1.2, the stages of the aircraft development process covered by each environment shall be evaluated. This also allows to see how many environments constitute comprehensive design programs as mentioned in subsection 4.4.5, which is an aspect related to multi-fidelity considerations.
- 2) **Aircraft type:** as mentioned beforehand through the thesis, different types of aircraft may require distinct analysis and design procedures due to applicability

considerations. A first distinction will be made between manned and unmanned aircraft. For manned aircraft, these shall be categorised in civil and military, and the first ones shall be further classified depending on their category: VLA, normal, and transport. This criterion is related to the aircraft overall size and also to the associated certification codes. Both of these aspects influence the design procedures both due to applicability aspects and also due to the influence of airworthiness considerations in the design space, as introduced beforehand in this thesis. For unmanned aircraft, a size classification shall also be considered, as it has been highlighted that design and analysis process can greatly vary between small RPA and larger ones [115]. In this case, as it was seen in chapter 3, the regulations are not only related to aircraft MTOM but also to operational aspects, so establishing a link between aircraft size and certification category is not as straightforward. Furthermore, due to the heterogeneity in the design and operational scope of the regulations, as seen in subsection 3.5.2, establishing uniform boundaries for a regulatory classification is hindered. Thereby, in for this aircraft type, the classification shall focus on the overall size of the RPA. More comments are given further below in the text.

- 3) **General arrangement the aerodynamic surfaces:** here, the possible configurations which the design packages can analyse shall be evaluated, which is related with the unconventional configuration trend as well as with the general descriptive capabilities of the software. As laid out beforehand within section 4.3, a distinction shall be made between those environments which showcase both geometric representation and analysis capabilities, and those which have demonstrated to be able to represent the geometry of a particular layout, but their application in different discipline analysis has not been demonstrated in the consulted references.
- 4) **Powerplant type:** the different types of powerplants which are covered within the capabilities of the design environment are included in this classification. This does not only describe the overall scope of the environments, but also links with unconventional vehicle and RPA design.
- 5) **General software capabilities:** This broad category includes the features associated with the trends and challenges analysed within the previous review, as identified beforehand within this section. These include:
 - a) **Compatibility with central aircraft data models:** this includes both data schemas such as CPACS, ADML, and ADDAM, and also any other possible structured and formal ways of data modelling, for instance through a common database or language. As long as the software is compatible with the format and can import and export data according to it, the feature has been considered to be present.

- b) **External software interaction and integration:** refers to both the possibility of connecting the design package flow with external specialised analysis software, as well as that of integrating these software within the design package itself, as mentioned in relation to the interoperability trend.
- c) **Flexible design workflow:** this covers the possibility of the package to alter the order of the tools and analyses within its workflow to adapt to distinct design approaches, which was commented within subsection 4.4.2 to be the second kind of flexibility enabled by a modular approach. This is in contrast to method flexibility, which is considered separate, and is instead related to modifying the analysis process within each module without altering their order.
- d) **Distributed and collaborative environment capabilities:** this feature includes various possible options which augment the capacity of conducting design and analysis tasks in collaborative and distributed environments, as seen in subsection 4.4.3. These many include workflow management, distribution of competences to different stakeholders, parallel run time of tools in distributed computers, etc. Legacy environments which have been integrated within other frameworks as modules themselves, by connecting their inputs and outputs to compatible tools or routines, would not be considered to have this capability, as the tool itself is serving as a module within the integration framework, instead of the environment constituting or managing the framework itself.
- e) **Method flexibility and multi-fidelity options:** refers to design packages that allow a certain degree of freedom to the user with respect to the analysis and design methods to be applied. This is linked to the possibility of changing the disciplinary analyses within the same module while maintaining the workflow, as mentioned beforehand. Following the criteria commented in subsection 4.4.5, multi-fidelity is considered a particular case of overall method flexibility.
- f) **Trade studies:** this capability has been considered when the environment offers specific tools and options to aid in the comparison of different design alternatives for the same set of initial requirements. This is mainly focused on distinct layouts and powerplant selections, so as to evaluate the advantages of some configurations with respect to others. It should be highlighted that parametric studies that analyse quantitative variations of certain variables on a specific configuration have been considered to fall outside the scope of this feature, which is instead related to major qualitative decisions between different design concept solutions.

- g) **Mission definition flexibility:** this feature consists in the design environment offering the user sufficient mission modelisation options to allow to represent different mission types within the same framework, such as cargo transportation, ISR, SAR, etc. This is a valuable asset for all aeroplane types, but it is particularly remarkable when considering the trend of RPAS design as commented in subsection 4.4.7, due to the diversity of operations that these aircraft can accomplish, and would also constitute a fundamental characteristic for multi-role RPA sizing.
- 6) **Disciplinary modules:** here, the different modules representing distinct disciplines of analysis available within the design environment shall be classified, so as to offer an overall count of how many design packages have integrated methodologies related to each discipline.

Finally, it is highlighted that many of these features, particularly those within the category of general software capabilities, also represent overall desirable characteristics for computerised environments as previously identified within the state-of-the-art. Some of these looked-for characteristics as highlighted in previous references include flexibility to adapt the tool to different problems, overall versatility, broad scope of possible design concepts to be considered, and ease of updating of the environment, among many others (51; 91).

4.5.2. Trend analysis for state-of-the-art design environments

Having defined the features of design environments to be evaluated, this subsection covers the assessment of the prevalence of the aforementioned characteristics within existing design environments. The main process of the state-of-the-art assessment conducted here consists in counting how many design environments among the ones studied in this chapter present each of the capabilities laid out in subsection 4.5.1, so as to then analyse and discuss the results. The main purpose, as laid out previously within this chapter, is to provide an updated image of the current state of design packages, which will also allow to evaluate the current situation in relation to the trends and challenges analysed in section 4.4, with the overall conclusions in this regard being summarised in subsection 4.5.3.

Most of the hypotheses employed in the assessment process to be expounded here have been laid out beforehand in section 4.3. As commented at that point, the information has been obtained from the open literature, due to the proprietary nature of many design environments. This has also influenced the number of design packages for which sufficient information has been found, but nonetheless a relevant volume of data has been gathered for many design environments which are experiencing a noteworthy development nowadays. Overall, it can be considered that the set of suites which have been included here constitute a representative sample of the overall paradigm, with

emphasis on recent design environments and those which have seen a noteworthy update effort through time.

A relevant criterion employed in the assessment, which was already commented beforehand, is that it is only considered that a design environment has a certain capability if it has been explicitly documented or demonstrated within the state-of-the-art references that have been found. This means that it cannot be ruled out that there would be a larger number of design environments showcasing certain features than that which has been included here, due to those aspects not being documented in the open literature. For instance, in some cases an explicit account of the layouts that the environment is able to size is not given in the consulted documents, so only those configurations for which design application cases have been found are considered here. To ensure that all the information of the design environments is accounted for, access to the source code would be required, which as mentioned beforehand, has not been possible within the scope of this study.

In spite of the aforementioned challenge related to the lack of explicit data on certain aspects, a suitable volume of information which allows to evaluate the main features laid out in the previous subsection has been found of a total 27 computerised design environments. Considering the relevance of the aspects related to RPA design in the context of the thesis, these have firstly been classified attending to whether they can perform analysis and design tasks on either manned or unmanned aeroplanes, or on both types while using the same environment. The results are shown in Figure 4-9.

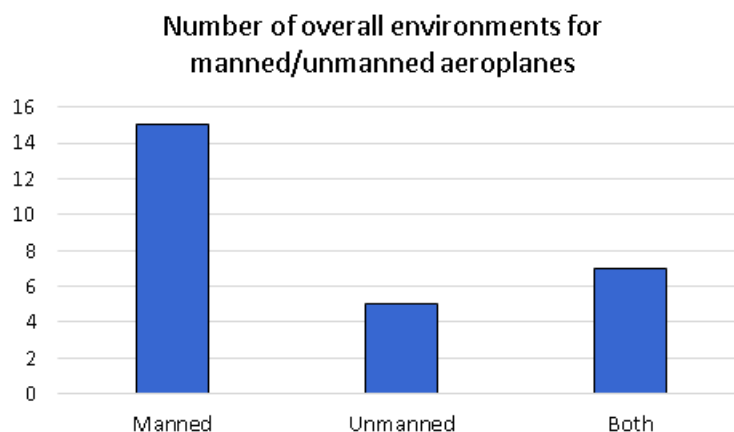


Figure 4-9. Number of overall environments including analysis and design capabilities for manned or unmanned aeroplanes, including those which cover both types.

These results include the design environments exclusive for RPA design which were already compiled and commented in the overall review of chapter 2, which have in some cases been integrated within previously existing environments with a broader scope. At this point, it is noted that, in some cases, design environments covering both manned and unmanned aeroplanes have reused the same types of methods for both aircraft types. This

can be understood as most of them have been developed primarily with manned aeroplanes in mind. This aspect links with one of the challenges of RPA design as expounded in section 1.3, which relates to the potential lack of applicability of manned aircraft methods within the realm of RPAS. In the case of higher fidelity approaches that might be more generalisable, this issue may be mitigated, but specially for rapid design methods and medium-fidelity ones, it is usually preferable to develop new methods or to adapt existing ones to tailor them to the peculiarities of RPA. Albeit the direct reuse of manned aircraft methods is also present in design packages which have been particularly developed for RPA, it has been observed to a lesser extent in this area, where it is instead seen that there is a higher emphasis on specific methodologies tailored for RPAS.

On the other hand, there are also some computerised environments which cover both aircraft types that have implemented different approaches for each kind of aircraft, with certain capabilities of the environment even showing significant differences when it is employed to design one aircraft type or the other. For instance, certain disciplines might use an external software for manned aeroplane sizing, whereas an alternative design approach which has been implemented within the core of the suite is employed when performing the design of RPA. Other more general aspects can also be affected, such as some design environments covering both design phases for manned aircraft, but only one of them if they are to be used for RPA. Considering these discrepancies, for some of the aspects to be assessed below, classifying the design environments in the above three groups might not capture all of the relevant information.

Thereby, depending on the features which are being assessed at each point in this review, the design packages which cover both manned and unmanned aircraft design might be divided between the suite functionalities applicable to one aircraft type and the other, instead of by overall design packages themselves. Therefore, two classifications shall be employed in parallel:

- 1) The first one, by “**overall design environments**” analyses the features of interest in the whole package. Three groups might be employed depending on whether the suite can design manned or unmanned aircraft, or both, as seen beforehand.
- 2) The second categorisation shall focus, instead of on the overall packages, on “**design environment functionality areas**”, grouping those related to either manned or unmanned aircraft. The first category shall include all environments specific to manned aircraft and also the functionalities pertaining to this aircraft type of those packages that cover both kinds, with the same principle applying to unmanned aircraft functionalities. Attending to this, the first group will have a total of 22 elements, whereas the second one shall have 12, since the seven environments covering both aircraft types according to the previous classification are divided between both kinds of functionalities and added to the suites specific to each kind of aeroplane.

(a) Phases of the design process covered

This constitutes the first of the features laid out in subsection 4.5.1. Following a similar perspective to that of the review of chapter 2, it will allow to see if certain design stages present gaps with respect to others within the current landscape of design frameworks. Furthermore, it also ties in with the multi-fidelity trend commented in subsection 4.4.5, as one of its main purposes is the development of comprehensive design environments. In this case, as differences have been detected for the same design package between different functionalities, the second classification expounded above has been employed. For instance, some design environments only cover the preliminary design of RPAS, while both stages are considered for manned aeroplanes. The results are shown in Figure 4-10.

It should be noted that this feature is not explicitly stated in many of the references which have been consulted. Thereby, the functionality areas have been classified attending to the background of the design stages provided in subsection 2.1.2 while considering the overall goals and methods employed by the environment for each type of aircraft. In many cases, the boundary between preliminary and detailed design is blurred, particularly with the recent emphasis in the use of high-fidelity approaches in overall optimisation frameworks, so these two stages have been jointly considered.

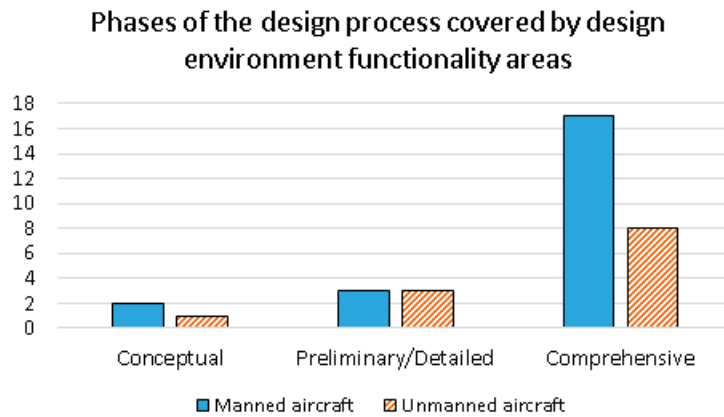


Figure 4-10. Phases of the design process covered by each design package functionality area when separating by manned and unmanned design aspects.

As it can be seen, there is a higher emphasis on the advanced design stages rather than on early ones, but the main trend is towards the environments being comprehensive, which coincides with the trend highlighted previously in subsection 4.4.5 as seen in previous research (51; 76). These holistic frameworks tend to employ convergence loops in the conceptual phase to ensure the adequacy and coherence of the concept obtained in the first design iteration, whereas the preliminary design workflow includes an optimisation process adding additional disciplines (41; 17). These trends are also observed in environments which are focused on each of the different design stages (61; 70). The

emphasis on comprehensive design environments further supports the recent efforts in the field of multi-fidelity approaches, and coincides with the remarks given by previous authors which discussed that the purpose of developing this type of frameworks would lead to a greater research in multi-fidelity method flexibility and on maintaining the same digital thread of the vehicle along its development (51; 100).

Even though the conceptual design phase is also covered by comprehensive design environments, it should be highlighted that it has received comparatively less attention to the preliminary stage, which is a trend already highlighted in previous works (51; 76). This be explained considering the higher computational effort required in later stages, and thus the greater comparative efficiency improvements which may be achieved by automating certain interoperability and workflow aspects. However, as a result, there is room for improvement in certain capabilities related to rapid sizing methods, along with their applicability and flexibility, as it will be mentioned further along this assessment. A relevant matter which complements the information of the aforementioned figure would be the extent to which current environments cover the tasks related to the overall initial sizing process as laid out in subsection 2.2.3, which constitutes a noteworthy set of tasks in generating a first overall definition of the design and the main elements of the overall aircraft through rapid methods. Whereas within the environment functionalities of manned aircraft the steps of this process are covered by a certain number of packages, this is seldom the case for those of RPAS. As a matter of fact, many computerised environments covering both aircraft types present initial sizing approaches for manned aircraft, allowing the user to reach a conceptual definition through established procedures starting from the initial requirements, but for unmanned aircraft an equivalent process is not provided, and an initial geometry must be directly entered by the user in the program without a methodological process generating it.

On the other hand, the ways and degrees to which existing environments which are specific of RPA cover the initial sizing steps presents significant variations. For instance, in the case of CCADE, from the mission requirements a matching diagram method is employed, which is usually among the typical approaches used in the initial sizing process. This gives the main wing and power characteristics. In contrast, it would appear that a methodological process for sizing the tail surfaces based on typical values or stability and control criteria at the conceptual level is not considered at this point. Instead, an initial sketch of these elements is given as an input by the user, so as to then enter an iteration and optimisation loop along with other disciplines (70). Regarding the design environment developed in (17), the first definition of the vehicle is not obtained through an initial sizing process, rather it is given as an input directly by the user. Then, if it does not comply with the requirements, it is resized by the program following an iteration loop. In other cases, such as the DECODE environment, there is a specific module for concept design which seems to integrate the initial sizing tasks (137).

Overall, there is a significant variety regarding conceptual design approaches for RPA, and initial sizing processes are seldom found within current environments which integrate statistical approaches, matching diagram procedures, and integral performance-based sizing, as it is proposed in the context of this thesis. The reasons substantiating this were discussed previously in the review of chapter 2, and are mainly due the relative lack of available methodologies of the GDM type when considering the combination of the aforementioned areas, so if these approaches are not available at the conceptual level, their implementation in design environments is hindered as a result.

(b) Aircraft types, general arrangement, and powerplant type

With respect to the aircraft types which can be designed and analysed by the environments, and albeit a first classification was considered at the start of this subsection, the more thorough one proposed in subsection 4.5.1 shall be employed. Most design environments can address the development of various aircraft types. The results are shown in Figure 4-11. For manned civil aircraft, the classification includes the applicable regulations for normal and transport category aircraft, as it is also found in this way within the open literature. This can be explained due the different airworthiness regulations in each case resulting in distinct restrictions to the design space, further highlighting the relevance of the airworthiness-based categorisation in the realm of manned aeroplanes.

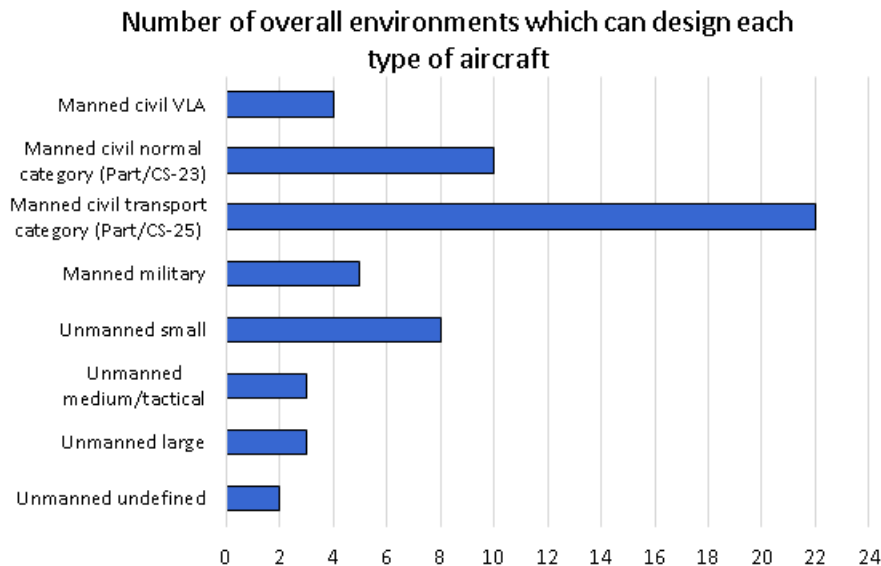


Figure 4-11. Number of overall design environments which can conduct analysis and design tasks for each aircraft type. For the “unmanned undefined” category, the authors of the package have stated that it can size RPA, but no further details on size or mass range have been given.

In the field of manned aircraft environments, it can be seen that all of the 22 functionalities covering this aircraft type cover the sizing of transport category aircraft, which is the main objective of many of these design environments (87; 223). Other manned aeroplane types

have received comparatively less attention, and they usually correspond to additional features of the software, with the main focus being transport ones. These other kinds of aircraft usually require adapted methodologies due to their singularities (8; 9), as mentioned beforehand through the thesis, with possibly the most noteworthy case being military aircraft. This is most clearly seen in design manuals such as those of (8; 9; 11), where there are remarkably distinct methodologies and empirical values employed for each aircraft type. Therefore, it is clear that the area of manned commercial transport aeroplanes is addressed by the vast majority of software, but there would be room for improvement for other types of aircraft within this area.

In the case of unmanned aircraft, as mentioned beforehand, the classification which has been employed here does not present quantitative boundaries. This is mainly due to the original references not stating a precise applicability range of the tool, with terms such as “*small RPA*”, “*medium RPA*”, and “*large RPA*” being employed to describe the scope and objectives of the environment. Thereby, even if a single set of boundaries in MTOM range were to be proposed in this survey, it would not be possible to determine with accuracy if a certain environment falls within one or various categories. Therefore, the design package functionality has been classified mostly attending to the RPA types covered as stated by the authors. Nevertheless, in view of the application cases showcased in the original references, it can be seen that the comparatively qualitative classification employed here would be coherent among the different environments. Most packages within the category of “unmanned small” perform design tasks on aircraft below 25kg of MTOM (61; 137), whereas those in the “unmanned medium/tactical” category showcase application cases of aircraft in the 100-500kg MTOM range (17; 35), and those in the “unmanned large” category performing the design of RPA above 500kg (35), even reaching the HALE type of RPA (133).

Once again, as in the case of manned aircraft, these categories have been separated since the methodologies applicable to each type can be notably different. This is highlighted by the authors of the environments themselves, particularly when they have developed design packages particularly tailored for RPA, as there can be significant variations in mission types, which at the same time influences powerplant choice, take-off and landing methods and restrictions, and applicable empirical relationships, among many other aspects (17; 61; 70; 137). Considering that there is a total number of 12 design environment functionality areas for RPA, it is seen that none of them cover all of the RPA kinds simultaneously. This can be explained when considering, as mentioned above, that each type is expected to require their own set of methods and considerations, and also when taking into account the additional hurdles in terms of conceptualising specific design methodologies which must regularly be tackled when developing these environments, as the overall area of RPA design methods is much less mature than that of manned aircraft as seen in chapter 2.

It may be worth to analyse how these trends compare with the current landscape of existing fixed-wing RPAS designs. In view of previous works which have compiled and analysed RPAS databases, it is seen that small and medium size ones are currently the most common. The number of large RPAS is remarkably lower, with very few aircraft being seen over a value of MTOM of 1000kg. Therefore, it could be expected that there would be more computerised environments focused on the sizing process of medium size RPAS, as at least in the area of fixed-wing RPAS they are almost as common to those in the small category. In contrast, the number of design environments covering them is equal to that of large ones, which have as of now been deployed in much lesser numbers. This may be due to medium size RPAS potentially requiring a larger effort to derive specific methodologies for their analysis and design, as in comparison large RPAS may potentially be comparable to manned aeroplanes in the VLA and normal categories, so already existing approaches available for these manned aircraft could potentially be adapted with less difficulty. Therefore, it can be considered that there is a certain mismatch between the areas of focus in design environments and the landscape of existing RPAS designs, which may constitute an area showing room for improvement in the development of future packages for the design of RPAS.

Furthermore, and connecting with the previous point, it should be mentioned that the comparative lack of methods for VLA (and to a certain extent, normal category aeroplanes) in the manned aircraft area, can also result in a lower synergy with RPA sizing approaches. This is due to the design methods for those types of manned aeroplanes being potentially closer to the ones required for RPA, at least when compared to the design procedures of transport aircraft, as for these latter ones, the differences between both aircraft types even when also comparing them with large RPA tend to be much more noticeable.

Moving on to the number of computerised environments which can model distinct aircraft layouts in term of lifting surfaces and their positioning, in this case all of the environments are analysed altogether. For this feature, a distinction shall be applied on whether, for each configuration, the environment only covers geometric representation capabilities or rather it also includes physical analysis and modelling capabilities. This consideration was introduced and substantiated in section 4.3. The can be seen in Figure 4-12.

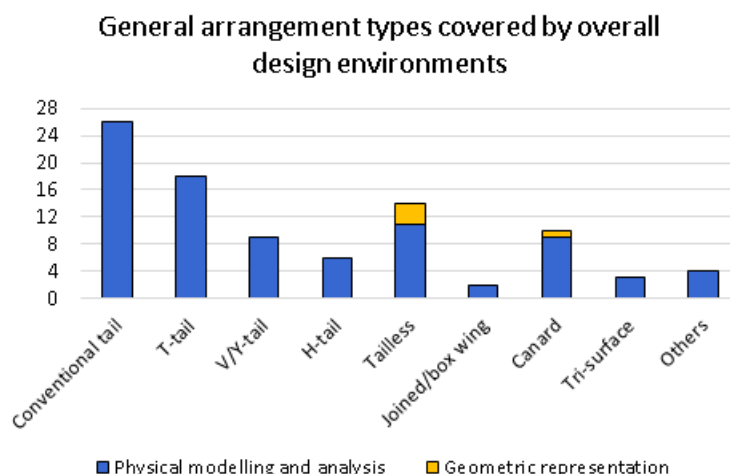


Figure 4-12. Number of design environments with capabilities related to different general layouts of the aerodynamic surfaces, either with demonstrated disciplinary analysis or geometric representation.

The prevalence of the conventional tail layout, which is present in nearly all of the design environments covered in this survey, is aligned with the results seen beforehand in this assessment. This layout is the most usual one, along with the T-tail, for transport aircraft, which are the most extended aircraft type in the realm of manned aircraft environments, and while this is not the most common configuration in the field of RPA, as it will be seen in chapter 7, it is still seen there with certain frequency. This line of thought also substantiates the T-tail being the second most common configuration compatible with present-day design environments.

The other configurations can mostly be considered to be unconventional layouts, thus connecting with the trend expounded in subsection 4.3.6. Overall, they are less frequently considered in design environments when compared to the previous ones. Special attention has been given to the tailless configuration, as this layout has been regarded to be a potentially more efficient alternative to conventional aeroplanes, thus its study represents one of the most relevant current lines of research in the overall realm of aircraft design, with both rapid methods and higher fidelity approaches having been investigated for its analysis (60; 257). The canard configuration also stands out, with some software offering the option of employing this type of aerodynamic surface in place of the classic Horizontal Tail-Plane (HTP).

However, the number of environments which consider other configurations, such as V/Y-tail, H-tail, joined/box wing and tri-surface aircraft, is comparatively low. When taking into account that in the field of RPA both the V-tail and H-tail layouts are the two most frequent ones, as it will be seen within chapter 7, there appears to be a mismatch between the capabilities of current environments and existing RPA designs. Therefore, this constitutes a noteworthy area of improvement towards the development of design environments for RPA so that more of them can offer the designer a set of representative alternatives which are aligned with configurations that are currently employed in these

aircraft. In the case of joined wing, box wing, and tri-surface aircraft, they are as of yet uncommon both in the fields of manned and unmanned aircraft. Overall, it can be considered that the comparative prevalence of each unconventional configuration in current design environments reflects the extent to which they are also being studied within the state-of-the-art of the wider aircraft design realm. In any case, the study of a wider range of unconventional configurations constitutes another area of interest for both manned and unmanned computerised design environments, especially when seeking to achieve more efficient alternatives be it for commercial air transport aircraft or for RPAS.

In terms of the design environment as a whole, the update of their capabilities to cover other layouts is not straightforward. Even if most of these configurations mainly affect the tail surfaces, the distinct considerations in terms of mass estimation, structural analysis, stability, and aeroelasticity, among others, can greatly influence the overall sizing and optimisation process. In addition, many of them, such as the H-tail, may imply additional changes to the overall configuration such as engine relocation. Thereby, and as expounded in subsection 4.4.6, it is expected that specific adaptations and models will be required for their consideration, especially both in rapid and medium fidelity approaches. This is another reason for the hypothesis of differentiating geometric representation and analysis capabilities, as even if an environment offers the option to create a geometry of a certain layout, it may not mean that particular adaptations required to perform its analysis have been implemented. This discrepancy between geometry and analysis capabilities only appears uncommonly, as seen in Figure 4-12, and only affects tailless and canard layouts. As seen in the references, this is mostly due to external software having been employed which include the capability of generating geometries of these configurations, but in contrast, the core functions of the software have not yet been adapted to their analysis, as expounded in section 4.3. Nevertheless, it is highlighted, as mentioned beforehand, that there could be larger number of environments compatible with these configurations, but only those which have been explicitly documented or demonstrated as being part of the analysis options of each environment have been considered here.

With respect to the types of powerplant that existing environments can modelise, this aspect has been quantified in Figure 4-13. In this case, since there are significant differences between the functionality areas of manned and unmanned aircraft design, even within environments covering both, this classification has been employed.

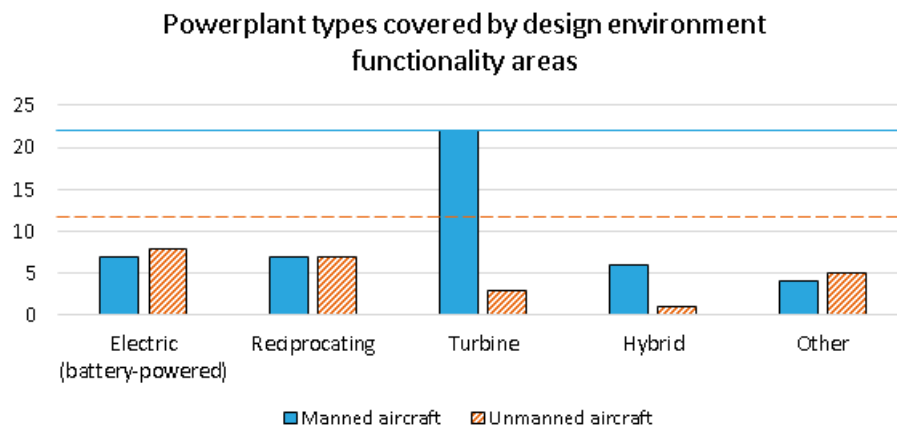


Figure 4-13. Number of design package functionality areas compatible with the modelisation of different powerplant types. The horizontal lines represent, following the same criteria as the bar legend, the overall number of design package functionality areas for manned and unmanned aircraft.

When considering the functionality area of manned aircraft design, the foremost powerplant type is that of turbine engines. Once again, this is aligned with the main interest in this area being on transport aircraft, since they are mostly equipped with this type of engine. The attention given to other engine types in this functionality area is remarkably lower, since electric, reciprocating, and hybrid powerplants would nowadays only be applicable to VLA and, at the most, normal category aeroplanes, which as seen beforehand, are aircraft types that are not being considered as much in the current landscape of computerised environments.

Moving on to the field of RPAS, the situation is remarkably different, as only a few environments include the option to size RPA with turbine engines. Albeit the number of design packages considering electric, reciprocating, and hybrid engines is close to the corresponding numbers seen in manned aircraft suites, when considering the prevalence in relative terms with respect to the overall number of package functionality areas for each aircraft type, these kinds of powerplant represent here a much more noticeable proportion. This is in line with the current design trends of RPA, as aircraft with reciprocating engines and electric motors are the most common ones, with those equipped with turbine engines being comparatively uncommon, and it is also aligned with the distribution of current RPA designs in the different size ranges and the types of powerplants with which they are equipped. These trends in existing designs have been seen in previous works analysing RPA databases (36; 39), and they will also be substantiated within this thesis through the statistical trends that will be presented within chapter 7 as obtained from the database developed as part of this research. Therefore, in contrast with the previous two features, where mismatches were seen between the trends in current designs and those of computerised environments, here both areas of research and current practical deployment appear to be aligned.

Current design environment capabilities in terms of hybrid engines are comparatively marginal. In relative terms, these have received somewhat more attention in the area of manned aircraft, which fits with the fact that this engine type is mostly being studied for environmental reasons, and the largest emphasis in terms of emission reduction is nowadays on manned aircraft, rather than on RPA. The “Other” category includes hydrogen powerplants, rocket engines, and electric aircraft powered by solar engine, among others. These uncommon powerplants have been studied to a greater extent in RPAS as seen in the graph above, possibly due to the nature of these aircraft being more aligned with experimentation and prototyping. In any case, all of these types of powerplants, including the hybrid ones, have not yet seen extended use neither in the manned or unmanned aircraft realms, but it is seen that there is an interest in investigating their feasibility through their consideration within current design environments.

(c) General software capabilities

The group of features associated to this category are mostly related to the main trends in the area of computerised environments as analysed in the review of section 4.4, so the results presented here show noticeable connections with aspects mentioned beforehand. In some cases, the same design package covering both manned and unmanned aircraft design shows dissimilar capabilities in relation to these features, so once again the classification attending to functionality areas has been employed when analysing most of the capabilities, whereas the one related to method flexibility and multi-fidelity has been analysed considering the classification by aircraft type. The results are illustrated in Figure 4-14.

The first capability, that of compatibility with a common data model, has seen a rapid expansion in recent times with the adoption of formats such as CPACS. This is seen in the trend for manned aircraft functionality areas, where nearly half of the packages which have been evaluated present this characteristic, with most of them being modern environments such as CEASIOM (238), FAST (90), AGILE (92), and ADEBO (41). Even in the case of recent suites which in their origin have not integrated this capability, such as SUAVE and GENUS, the authors state that they expect to add functionalities in this regard in future revisions (59). This showcases the increasing interest in this trend, which can be expected as it was seen beforehand both in the review of 4.4 as well as in the summary presented in Figure 4-8 that it serves to enhance many other aspects which are also of remarkable interest, such as interoperability, extensibility, and collaborative design. Albeit in the area of RPAS design these formats have been comparatively less implemented, there is also a noteworthy interest, as in the case of ADDAM, which is a format compatible with RPAS (41), and also in other approaches for data modelling shown by environments specific to these aircraft such as in the case of CCADE (70) and DECODE (137). An extension of currently available common formats, as well as the

development of new ones, focusing on the peculiarities of RPAS, could potentially constitute a remarkable asset for the expansion of this capability for this aircraft type.

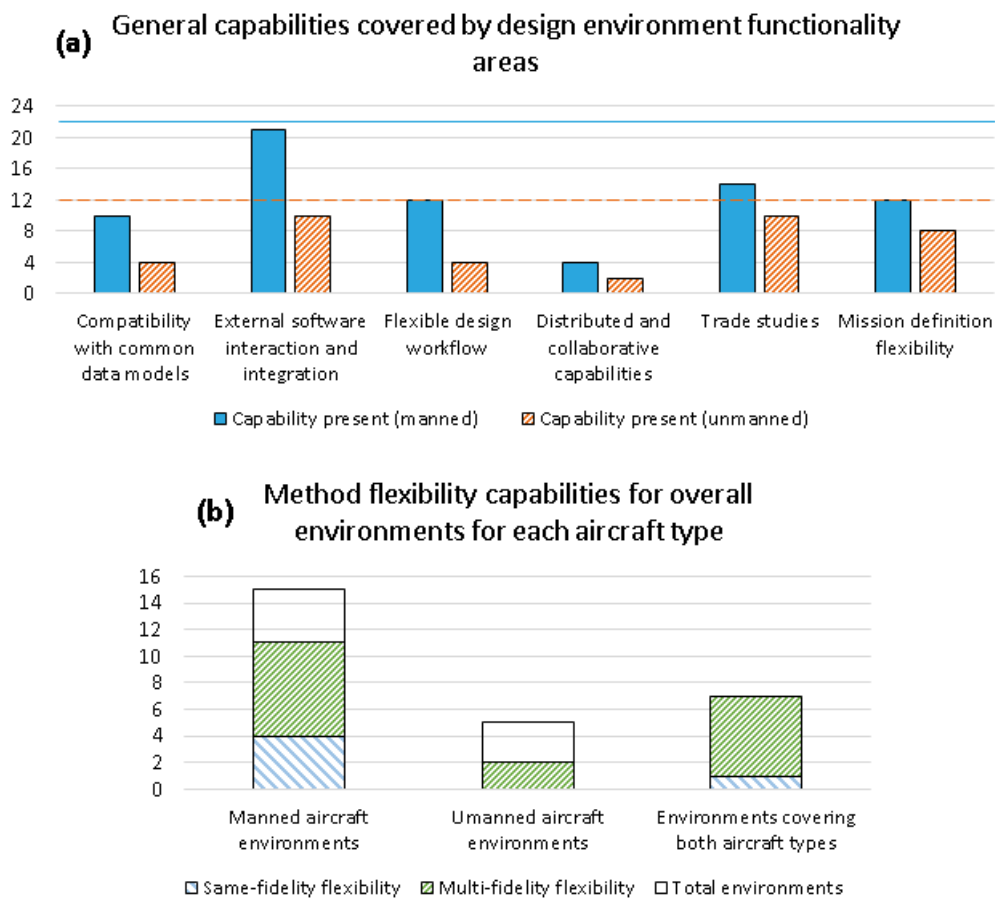


Figure 4-14. Number of design environments/funcionality areas presenting each of the general design software capabilities. (a) Showcases the number of functionality areas which present the different capabilities save for method flexibility and multi-fidelity. The horizontal lines represent, following the same criteria as the bar legend, the overall number of design package functionality areas for manned and unmanned aircraft. (b) Illustrates the number of packages grouped by aircraft type showcasing method flexibility and multi-fidelity capabilities.

With respect to the features associated with the second trend, that of modularity, interoperability, and integration, it was mentioned in subsection 4.4.2 that a modular organisation of the disciplines within the design environments has been a mainstay of most design environments, from those such as FLOPS (86) to recent ones such as SUAVE (93) and LEAPS (91). This fits with the organisation of the aircraft design tasks in steps related to different disciplines, as seen in the overall realm of aircraft design as it has been commented through this thesis. The capability of external software interaction and integration is also remarkably extended amongst the environments which have been analysed here, being present in the majority of functionality areas both for manned and unmanned aircraft design. As discussed through subsection 4.4.2, this area has been noted by some authors (59; 68) to constitute a great benefit in the development of these

environments, as they can cover capabilities not included within their core program through the use of specialised and proven disciplinary analysis software. If an adequate interface is established between the design program and these external tools, the corresponding modules do not need to be developed by the design package creators, allowing them to focus on the interfaces and the influence of these analyses in aircraft sizing and optimisation.

In comparison, there is a greater room for improvement in terms of design workflow, which as mentioned in section 4.4 has been considered by some authors to be as important as the fidelity level of the methodologies themselves, and can potentially constitute a fundamental asset towards adapting the design process to the development of unconventional layouts (51; 155). In relative terms, so far this capability is present to a higher degree in functionality areas related to manned aircraft design, perhaps owing to the greater maturity of this field, and so far most of the RPAS functionality areas which integrate it have accomplished this due to being within design environments covering both aircraft types where this characteristic is already present for manned aircraft design. It should also be highlighted that this capability can not only constitute a remarkable asset towards unconventional vehicle development, but it can also aid to adapt the design process to distinct sizing philosophies and different sets of initial specifications, providing overall a greater flexibility to the designer when addressing dissimilar design tasks.

Moving on to distributed and collaborative capabilities, this constitutes one of the areas with greater potential for improvement within the current paradigm of design environments. In spite of the rising needs for these options, as commented in subsection 4.4.3, so far only a few environments present them, and these are mostly recent efforts such as AGILE (222) and CCADE (70). Aside from the use of common data formats and integration frameworks, it has also been noted that Web technologies can constitute an essential enabler to implement these capabilities in further environments (70; 95), so further research in this area and its integration with current suites can be expected to aid in improving this capability in the future.

Albeit no specific characteristics were defined in subsection 4.5.1 for the extensibility trend, it was seen in the development of this area of work within subsection 4.4.4 and also in Figure 4-8 that many of the previously analysed features serve to enhance this area. In view of the common data model, interoperability, and workflow flexibility characteristics, which are all related to extensibility, it is seen that the current scenario is promising for the development of design environments which are more easily updated and expanded, as is the case of LEAPS (91). From the aforementioned capabilities, the one which perhaps further aid in design package extensibility is that of the common data formats, as it is comparatively less prevalent than the others, and these data models also tend to be remarkably extensible themselves, paving the way to increase the aspects covered by the models and methods implemented in the design environments which use them as a central data node. Focusing on RPA design capabilities, the use of extensible data

representations could constitute a great asset towards expanding current methods and suites which cover manned aircraft design so that they can integrate the added considerations, hypotheses, and data required for unmanned vehicle sizing.

Regarding method flexibility and multi-fidelity, it can be seen that this capability shows a noteworthy prevalence in the area of manned aircraft environments, with most of them showcasing a certain degree of method flexibility, be it for the same level of fidelity or for different ones. As a matter of fact, multi-fidelity options are remarkably widespread for this aircraft type, which is aligned with the fact that most current design environments seek to be comprehensive, as seen beforehand in Figure 4-10. This also fits with observations by previous authors, who highlighted that multi-fidelity methods would be required to enable developing holistic packages covering various design stages and allowing to maintain the same product digital thread through the process (51; 100). Comparably, these flexibility and multi-fidelity capabilities are less extended in the area of RPA design environments, particularly in those which are focused on these aircraft. In contrast, packages covering both manned and unmanned design benefit from applying this feature to both types of aircraft, as in many cases in these environments, the multi-fidelity capabilities are put into practice through the use of higher fidelity software (85; 223), which might require less adaptations to fit both aircraft types within the same suite.

From the viewpoint of the designer, higher flexibility allows to tackle more diverse aircraft design cases and to cover more possible aircraft types and design alternatives within the applicability range of the environment, which explains that characteristics related to this area are remarkably sought after. However, a more detailed analysis would have to be conducted to check whether this method flexibility is balanced through the different disciplinary areas or rather if it is mostly focused on a few ones. The information which has been compiled from the open literature for this survey would not currently allow to analyse this aspect in detail, which could constitute an avenue of future analysis.

Moving on to the trade study capability, it can be seen that, in relative terms, this characteristics is comparatively more extended within RPA design functionality areas than for the manned aircraft case. This is consistent with both the ubiquity of unconventional layouts in the realm of RPAS, as well as with the fact that this area presents a much higher diversity of configurations, as already laid out in section 1.3 at the start of the thesis. In this regard, it can be considered that current RPA environments are well suited to address the comparison of various layouts representing design concept alternatives, as commented in subsection 2.1.2. In the field of manned aircraft suites, this capability is still notably present, possibly due to the recent emphasis on unconventional vehicle design. This follows the trend mentioned in subsection 4.4.6 in relation to most design cases involving unconventional layouts usually comparing them with more typical ones, so as to assess whether the improvements in efficiency that can be achieved are worth the increased efforts in terms of design, analysis, and certification.

Finally in this category, and with respect to the mission flexibility feature, it is first noted that, albeit special emphasis has been placed beforehand on the usefulness of this characteristic for RPA design, it can also prove essential in the field of manned aircraft sizing. This is particularly true for military aeroplanes, which can also present a significant mission variety depending on the particular kind of military aircraft that is being considered (263). From a broad perspective, it can be seen that this characteristics is relatively widespread among the different design environments in both the fields of manend and unmanned aircraft. In relative terms, it is more prevalent in the latter, which also fits with the mission variety of these aircraft as already laid out in section 1.3.

However, the viewpoint provided by the graph should be complemented with a more detailed analysis of the extent to which mission flexibility is provided in the different packages, particularly since this point is strongly related to one of the main lines of research of this thesis, which is that of integral performance-based sizing with multi-role considerations. Taking a closer look at the realm of manned aircraft functionality areas, it is seen that most degrees of freedom allowed in mission definition are still restricted to the boundaries of typical transport aircraft mission flight profiles and laws. These may include, for instance, different criteria to establish the required Reserve Fuel (RF), or the definition of flight profiles with either constant height and speed or ones following a step-climb. However, save for very few design packages, further variations in flight law or flight profile geometry, such as the addition of ingress and egress segments, are generally not as extended. In any case, this fits with the main focus of design environments in this area being set on transport category aircraft, as it was seen beforehand.

In terms of RPA mission flexibility, the degrees of freedom vary considerably among the different design packages. In the case of those which share functionalities for manned and unmanned aircraft, in most cases, the same limitations as seen beforehand apply, so mission definition for RPA would mostly be limited to cargo transportation, which are those that are more similar to the ones of transport manned aircraft. However, some design environments such as ADEBO, which covers both aircraft types, do present a higher flexibility for RPA mission definition, covering other kinds of operations such as aerial photography or mapping, among others (114; 154). In the case of design environments which have been particularly developed for RPA, the mission flexibility tends to be higher, albeit the degrees of freedom which are allowed in each case depend of each individual suite. For instance, in the design package of (17), the designer is allowed to define various mission segments which when combined allow to model diverse operations such as hurricane tracking, but in all cases the flight law which must be employed is one where C_L is fixed at a specified value. Other studies state that the software offers flexibility in the mission definition but additional details are not provided, complicating a more detailed assessment of the specific capabilities that each one offers in this regard.

Considering the above, it can be seen that mission flexibility has many different dimensions which may be considered, with some design packages prioritising some degrees of freedom or others. However, in none of the cases which have been analysed save for one, which would be the RPA design functionalities integrated in the ADEBO suite (136; 114), have multi-role sizing considerations been observed. Here, these multi-role considerations have been considered within the preliminary design stage within an optimisation loop, so a gap would still remain in multi-role initial sizing. This further consolidates the observations made during the review of chapter 2, as well as the need to cover OBJ.3.3 within the context of this thesis, as it will be commented further below.

Overall, the capabilities analysed here do not only serve as key enablers towards enhancing trends such as method flexibility, unconventional vehicle design, and RPA design, but as noted beforehand, they are also key towards enhancing their operating efficiency, both in terms of setting up and or running the analysis and design procedures. This constitutes in itself a noteworthy line of research (12; 92), as mentioned through this chapter, and it becomes even more relevant considering the growing complexity of design procedures and of the environments themselves, as also commented through this review. In view of the current scenario, it can be seen that these aspects have been considerably enhanced in recent design environments, and it can be expected that this line of work will continue showing a remarkable development in the future.

(d) Disciplinary modules

The final matter to be assessed shall be the number of computerised design environments which include each of the main disciplinary modules that have been considered in this investigation. This aspect links with the stages of the design process covered by the design packages, as commented in subsection 2.1.2, and also provides an overall picture on the capabilities of the suite. A more detailed analysis on the models employed for each of the disciplines on each package would be outside the scope of this survey, since it is focused on overall trends as it has been commented beforehand. In any case, due to the lack of information on the open literature regarding the specific methods which have been implemented, addressing this type of analysis without having access to the source code of the environments constitutes a significant challenge. It is also highlighted that this analysis is focused on the disciplinary modules, as they are the ones which are more tightly related to the modelling and design capabilities of each suite. Other modules such as administration and management ones are outside the scope of this analysis. Nevertheless, the overall evaluation provided here allows to extract significant conclusions on the capabilities of the overall landscape of design environments.

In this case, dissimilarities have also been observed between the available modules even for the same package when considering the design of manned or unmanned aircraft. Thereby, once again the classification attending to functionality areas shall be employed. Additionally, and linking with interoperability considerations, a classification of the modules itself is proposed to differentiate those which are internal to the core of the suite,

those where the corresponding calculations are addressed by external software, and the cases in which both internal and external models can be employed, with this latter case generally being associated with higher flexibility levels, and even with multi-fidelity capabilities. Furthermore, for the airworthiness discipline, the cases in which certification considerations have been integrated in other modules has been considered, in contrast to those packages where there is a dedicated module for this discipline. The results are shown in Figure 4-15.

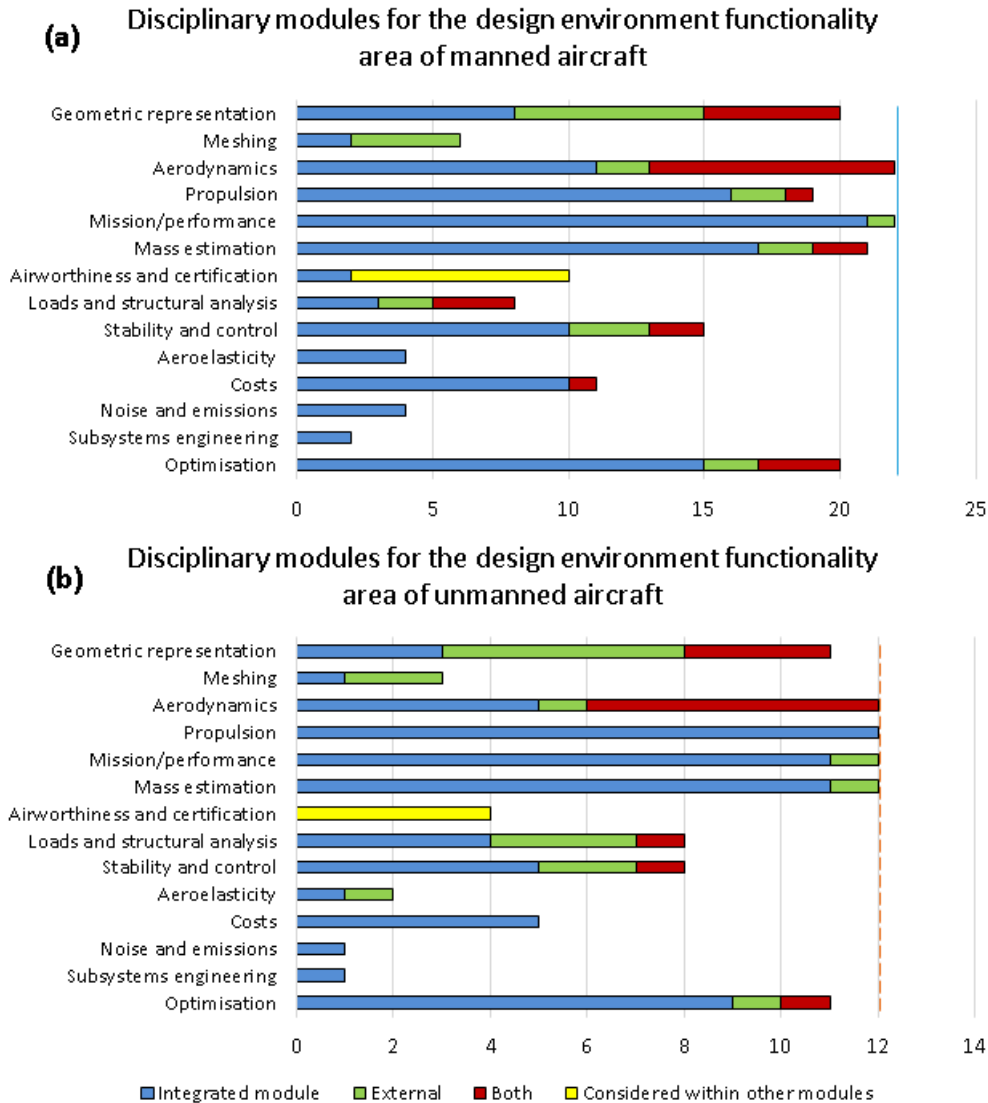


Figure 4-15. Number of design environment functionality areas presenting each of different disciplinary modules. The vertical lines represent the overall number of design package functionality areas for manned (continuous line) and unmanned (dashed line) aircraft. (a) covers the modules for the functionality area of manned aircraft, and (b) does the same for the area of unmanned aircraft.

An overview of the results allows to see that there is a significant unbalance among disciplines, which is a trend already seen in previous research within the field of manned aircraft design environments (63). However, the overall relative attention to the different

disciplines seems to be balanced between the manned and unmanned functionality areas when compared to their total numbers in each case. The relative prevalence of internal, external, or both kinds of modules also appears to be similar between both areas. Some particularities of each discipline in this regard shall be commented in the following analysis.

Before going forward, it should be emphasised that, within design packages covering both manned and unmanned vehicle design, for the latter type of aircraft, an overview of the available information on the specific methods employed reveals that there is a significant reuse of manned aeroplane methods. This trend was already commented beforehand, and as mentioned by other authors, depending on the case it could result in certain inaccuracies in the design results. It can be deduced that this has mostly been due to the main objective of these previous works being the development of the design package itself, rather than the development of novel design methods for RPAS. As seen in chapter 2, many areas of RPA design present significant gaps, so the combined effort of devising new methodologies so as to then implement them in the design environment could result in a lengthy process. Thereby, it can be expected that the focus of most works in this area has been on assembling a functional design environment instead of on developing novel methodologies, so the reuse of manned aeroplane methods has sought to expedite the development process. In the case of some design environments such as ADEBO (41), the development of specific methodologies for RPAS as well as their integration within the suite has spanned various years after the first version of the environment (114; 135; 154; 264), further reinforcing that covering both of these aspects is a significant undertaking. This direct reuse of methods for manned aeroplanes is less widespread in packages which have been developed specifically for RPAS. Furthermore, as noted beforehand in this text, the potential applicability and accuracy concerns are diminished when it is the case of higher fidelity methods, which might be more generalisable. This is the case of most external software used to cover disciplinary analyses.

The most frequent modules seen in both areas cover the basic disciplines in aircraft design of mission and performance, aerodynamics, weight estimation, and propulsion. These are common to both the conceptual and preliminary design stages, and are thus also required for comprehensive environments. With respect to the discipline of aerodynamics, the remarkably extended use of external software should be highlighted. This is due to the possibility of reusing the results of specialised and proven programs such as XFOIL, AVL, and PANAIR, among many others, which can be used for certain aerodynamic calculations, mainly those of lift distribution and vortex-induced drag. Furthermore, they are compatible with many different layouts, even of unconventional configurations as seen in (58; 85; 259). In many cases, their results must be complemented with other methods, usually semi-empirical approaches in case of conceptual design, to add other drag contributions to the overall drag estimation (17; 135). The use of these programs alleviates the need to develop specialised modules within

the core of the suite. In contrast, the other disciplines mentioned above tend to be addressed through internal modules.

Geometry representation also shows a noteworthy use of external software, which is motivated as geometry tools have become increasingly widespread due to their usefulness in allowing to visualise the whole aircraft at a glance and check how the changes in design or optimisation modify it (265). Most of these external programs are CAD software such as CATIA, and in many cases the OpenVSP geometry engine has also been employed, as it is more aligned with parametric representations which are typical of conceptual and preliminary design (68).

Special attention has been given in this assessment to the airworthiness/certification discipline, since it can not only be present through the full design continuum as commented in subsection 2.1.2, but it can also have a great impact in the available design space, which is another one of the central topics of the thesis, aligned with OBJ.3.2. Two cases have been analysed here: those design packages which incorporate a complete module dedicated to managing certification information, and those which integrate some criteria relative to applicable regulations in other modules. The former case is considered to be of special interest, particularly with the high degree of current integration with optimisation tools, since this module centralises certification requisites hierarchically in order to apply them to different stages in the design process in different ways, even serving as a database of certification requirements (90). Furthermore, this way of working would benefit the uniformity of the regulatory requirement input process within the design environment, as it is all done in a single place. In contrast, higher integration and interfacing work may be required, which can be eased through some of the approaches commented beforehand in this review, such as common data formats. So far, this approach has only been seen in the FAST (90) and RADE (248) design environments.

Regarding the second way of considering these regulations, it is to be expected that airworthiness requirements are present through various disciplinary modules, taking into account the connections between topical areas as previously seen in Figure 2-4. However, it can be seen that this discipline has been considered in a relatively low number of design environments, and even less so in the area of RPAS, so there would still be room for improvement in this regard. Furthermore, there is an additional aspect which should be commented here with respect to the four functionality areas of RPAS which have integrated this discipline, which is that none of them have taken into account specific regulations for RPAS such as those analysed through chapter 3. In these cases, the airworthiness requirements which have been considered for RPAS sizing have been extracted from manned aeroplane certification codes, such as the CS-25. Albeit the use of manned aeroplane codes to establish the certification basis for RPAS was considered in the EASA Policy E.Y013-01 of 2009, a tailoring of the code's requirements would still be required, which has not been observed in the application cases of these design environments. Furthermore, various regulations specific to RPAS have appeared since the

publication of the aforementioned Policy, as expounded in detail within the review of chapter 3. Therefore, it can be considered that both the introduction of airworthiness aspects in a wider array of design environments, and the use of regulations applicable to RPAS for their design would constitute two future lines of work in this area.

Regarding the relative lack of loads and structural analysis modules, this is also one of the possible fields of improvement upon the development of new design packages, particularly in the area of preliminary design. Previous studies have mentioned the advantages of integrating the structural analysis early in the design process (265). However, it is clear that the need of accurate description of the aircraft geometry which is required to carry out reliable structural analyses, as mentioned in subsection 2.1.2, may postpone more in-depth studies to further design stages, at which step the interfaces with CAD systems can be highly beneficial (265). These aspects have already been considered in some of the instances of design packages analysed here (68; 87; 266). Regarding the number of these modules in the case of RPAS, it can be explained when considering that almost most of the eight instances seen in this area actually correspond to shared approaches within those design environments which integrate functionalities for both aircraft types. Specialised structural analysis modules for RPA are still scarce, and would constitute a promising area of future work within this discipline, as already commented in the overall realm of RPAS design in the review of chapter 2.

With respect to stability and control modules, there is a significant amount of external software both in manned and unmanned aircraft applications. Most cases in the latter aircraft type, as in the case of structural analysis, represent reused methods for manned aeroplanes in those packages which cover both kinds of aircraft. Overall, there are two main approaches. The first consists in obtaining stability and control characteristics from external aerodynamic software such as AVL or Tornado (235), which can leverage to a great extent the same interfaces used for the aerodynamic module in these cases if external programs were also employed there. The second approach is based on either the development of simulation modules for accurate aeroplane dynamic behaviour modelling (135), or the use of external flight dynamics simulation software such as JSBSim. The tail surface sizing process is not usually covered in RPAS design software, and instead an initial geometry is defined by the user to enter an optimisation loop in the context of the preliminary design stage. This fits with previous comments given within this assessment with respect to the initial sizing process, and also with the findings from the review of chapter 2.

Cost modules are seen in some design environments, with most of their applications being based in methods given in design manuals such as those of (7; 8; 14). Even in the case of RPAS, these approaches have also been employed in most cases, albeit some other environments have developed their particular models, highlighting key differences in RPA pricing (61; 137). The instances of aeroelasticity, noise and emissions, and subsystems engineering modules are as of now comparatively scarce for both kinds of aircraft.

The ubiquity of optimisation modules can be substantiated when considering that most of the environments analysed here are comprehensive in nature, as seen in Figure 4-10, and they place particular emphasis in the preliminary design stage, which is usually conducted through an optimisation loop, substituting the convergence loops that are more typical of conceptual and earlier design design approaches. The use of external optimisers has been leveraged to a certain extent in both manned and unmanned aircraft environments. It should be noted that the extended use of optimisation coincides with the findings of the overall survey of RPAS design performed in chapter 2, where this was the topical area with the largest number of works.

Albeit most design packages are focused on the basic disciplines of aircraft design which were mentioned at the start of this disciplinary module analysis, it is seen that many different subjects can be considered within the current landscape of design environments, further highlighting the need to invest effort in interoperability considerations and substantiating the prevalence of this trend. Regarding module types, it can be seen that a higher proportion of external programs can be seen in the geometry modelling, meshing, aerodynamic analysis, loads, and stability and control disciplines. This may be due to the increasing specialisation and level of detail in current programs within these areas, which can be leveraged by integrating them in the environment, allowin the design package creators to focus on other modules. Furthermore, the ease of interfacing with geometric software has been greatly increased with the introduction of common languages such as CPACS (267). The extended use of external software in the area of RPAS can also be explained as these tools are often the same as used in the functionality areas of manned aircraft within the same packages, with these being in most cases medium or high-fidelity external software.

As a final point to highlight which is particularly relevant in the context of this thesis, which is focused on the initial sizing stage of conceptual design, it is seen that most of the disciplines involved in this step of the design process are present in current RPA environments. However, the fact that all of the related modules are present does not necessarily imply that the overall initial sizing process as described in subsection 2.2.3 can be carried out. In view of current RPA design packages, rapid methodological procedures for tail surface sizing would still be missing, and in some cases the full geometry of the aircraft has to be given directly by the user to start an optimisation process, without a previous initial layout sizing process. The possible reasons for the lack of specific methodologies which can aid to complete this design step have been discussed in chapter 2 and in this survey, with the main possible reason identified in the context of this thesis being the comparative lack of conceptual design methods for RPA in specific areas, and due to some particular gaps within them, such as those related with tail sizing. These aspects shall be discussed in more detail within the section 4.6, which addresses the discussion of current design package capabilities in terms of RPAS design and defines the key features which would be required to further tackle the challenges associated with the development of these aircraft in future design environments.

4.5.3. Summary of the situation of existing design environments with respect to current trends and challenges

The discussion provided along the assessment of the previous subsection has provided various insights regarding the extent to which existing design environments cover the current trends and challenges of this field as identified in section 4.4. This has mostly been done through an analysis of the prevalence of the different features associated to each trend as laid out in subsection 4.5.1, and also through some additional information compiled from the state-of-the-art pertaining to the aforementioned features, such as the number of modules which are internal or external to the core of the suite, or the different ways in which mission flexibility has been implemented.

This brief subsection provides a summary of the findings of the assessment in relation to each of the current trends and challenges, save for that of RPAS design, which will be covered in more detail within section 4.6, since it is more tightly related with the core topics of the thesis. The main information has already been expounded in detail within the previous subsection, so this one serves more as a wrap up of the main conclusions in each of these areas, which are given below:

- 1) **KBE capabilities:** the main feature analysed in this regard has been the compatibility with data models, including common data formats such as CPACS and ADML. Albeit the number of design environment which present this capability is somewhat lower when compared to other features, this area is rapidly expanding, with many modern software being compatible with these data formats, and others planning to add related features in the near future. Thereby, albeit currently there is still room for improvement, it can be expected that this area shall continue to expand. ADML already represents a format compatible with unconventional aircraft, and ADDAM with RPAS. Further extensions of these data models and added compatibility with different tools may constitute promising ways forward. Overall, it can be considered that this trend is remarkably dynamic and the current interest can be expected to accelerate future advancements.
- 2) **Modularity, interoperability, and integration:** overall it can be considered that this trend is more developed compared to others and that is related challenges are for the most part being effectively managed nowadays. Modularity has been present in design environments since their beginnings, and capabilities related interoperability and integration can be seen in most of the analysed design environments, as seen in Figure 4-14, also aided by the aforementioned common data formats. The maturity of the interoperability area can also be seen in the number of external disciplinary modules that have been identified in Figure 4-15. The area where there would still be certain room for improvement is that of workflow flexibility, particularly in the domain of RPA.

- 3) **Distributed and collaborative environments:** this is perhaps one of the areas which currently shows more margin of improvement, since it was seen in Figure 4-14 that very few environments, just close to 20 %, presented these capabilities. However, most of its upstream characteristics, such as common data models and interoperability, show promising developments, so it can be expected that with further research in particular aspects such as integration frameworks of Web technologies, the capabilities related to this trend can soon be more extended.
- 4) **Framework extensibility:** this trend is mainly related to previously commented features, such as common data models, software interaction, and modularity. Thereby, it can be considered that its current situation is also relatively favourable, with improvements in the previous areas potentially enabling further enhancements in extensibility. Many modern environments such as LEAPS (91) and ADEBO (41) place great emphasis on this characteristics and have demonstrated their capabilities in this regard, as seen for example in the successive updates to ADEBO integrating further RPA design methods.
- 5) **Method flexibility and multi-fidelity:** along with the trend of interoperability, this is perhaps one of the most mature areas nowadays, with a remarkable number of environments showing some kind of flexibility in this regard as seen in Figure 4-14. A more detailed analysis on the specific methodologies offered in each case could complete the assessment related to this trend, which would require further work mainly in the area of RPA design.
- 6) **Unconventional configurations:** along with that of trade studies, many of the previously mentioned features also aid with respect to the capabilities of this area. Therefore, the current scenario is favourable from an overall point of view, particularly in recent environments which have been developed with the purpose of developing these aircraft types. However, as seen in Figure 4-12, most of the effort has been invested in tailless layouts, with other unconventional configurations being comparatively neglected in the field of design environments, whereas in the overall realm of aircraft design some of them have shown remarkable promise in preliminary studies, such as the joined and box wing layouts among others (58; 219; 259). This would constitute a further area of work that would require the development of additional approaches for design of these aircraft and also further method flexibility to integrate them within the workflow.

In view of the above, it can be seen that, whereas the general situation considering all trends is favourable, they have not advanced at the same pace, with some showing more significant gaps than others. Considering the dependencies among the distinct areas as seen in Figure 4-8, and taking into account the higher effort which is being invested nowadays in software considerations, which are mainly related to aspects located upstream in the relationship chain, it could be expected that in the future the different

trends shall further level out, since advancements in the upstream trends shall enable further improvements in the ones downstream.

4.6. Discussion and key features towards future RPA design environments

This section addresses the third of the specific objectives of this chapter. As laid out in the section 4.1, the purpose here is to assess to what extent the current landscape of computerised design environments may aid to tackle the foremost challenges related to RPAS design. This does not only connect with one of the seven main areas of interest within the realm of computerised environment research as identified in section 4.4; but it also links with the core thread of research of the thesis on RPA design methodologies, and particularly it provides an answer to OBJ.2.2 of this thesis, which is focused on investigating the suitability of current design environments for their application in RPA design tasks.

Considering the above, and to accomplish the objective of this section, it is required to assess whether the capabilities of existing computerised environments already provide initial sizing approaches for the first stages of RPA design which can address the main hurdles that the designer faces when tackling the development of these aircraft. This shall be done through a comparison of the current challenges in RPA conceptual design, as identified in section 1.3, with the features of existing environments, as obtained from the review and trend analysis of section 4.5. In the case that gaps are detected within the current frame of design environments towards addressing the aforementioned challenges, a set of key areas of future work towards developing novel design packages which can cover those shortcomings shall be proposed. Thereby, the process is similar to that which was followed in subsection 4.5.3 for the remainder six trends related to computerised environments, albeit here more attention is given to RPAS since they constitute the main topic of this thesis, and the results from this assessment shall influence the development of novel design methodologies to be conducted within part III.

With this, subsection 4.6.1 provides a discussion on the extent to which the capabilities of current design suites provide an answer to the main hurdles of RPAS design. Then, in subsection 4.6.2, and in view of the gaps identified within the previous assessment, future directions of research are proposed towards the development of novel design environments for RPAS which can cover the foremost challenges towards the design of these aircraft.

4.6.1. Current state of design environments towards addressing the main challenges of RPAS design

The approach followed in this subsection shall be similar to that of subsection 4.5.3, where in view of the findings of the design package trend analysis provided in subsection 4.5.2,

a discussion was provided on the degree to which the current areas of work as identified in section 4.4 were covered by the capabilities of existing packages. Here, the focus shall be on the trend of RPAS design, with a particular emphasis on the extent to which the main challenges in the area of initial sizing approaches are currently covered, as this is the main topical area of this thesis.

The foundation to most of the aspects to be discussed here has already been provided through the trend analysis of subsection 4.5.2, where the way in which different features could affect RPAS design efforts was already expounded. Furthermore, as illustrated in Figure 4-8, the trend of RPA design links with many characteristics and features of the others, so the analysis provided in the previous section related to the remaining six areas of interest also constitute a relevant foundation towards the discussion to be developed here. Therefore, here the different findings provided beforehand shall be compiled and summarised, and most importantly, the way in which the current capabilities are aligned or elsewhere with the main challenges towards RPAS conceptual design shall be assessed.

In view of the above, and considering that the main focus is to see to what extent the current hurdles have been addressed by design environments, the guiding thread to the discussion provided here shall be based on the main challenges in RPA conceptual design as identified in section 1.3. The following list is based on that which was provided in the aforementioned section, where each of these issues were introduced, with the focus now being on the relationship of each of them with the features of computerised design environments and the current state to which these capabilities might aid in surmounting each challenge:

- **Variety in mission types/development of multi-mission aircraft:** the foremost design package feature contributing to this challenge would be that of mission flexibility. As seen in Figure 4-14, a majority of RPA functionality areas have implemented this capability to a certain extent, and the mission/performance disciplinary module appears in all of these functionality areas as shown in Figure 4-15. However, so far as detailed information was found in the literature, and when taking a closer look at the extent to which mission flexibility is considered in each environment, it was seen that there are considerable variations in the degrees of freedom provided in each case for mission tailoring, with many environments only allowing certain variations based on cargo transportation missions, which constitute only one of the many types of mission which RPAS can accomplish. Other suites allow to model different kinds of operations, but flight laws were restricted to only a certain type. Furthermore, none of the design environments have demonstrated multi-role sizing capabilities within the conceptual design stage. Thereby, taking a closer look at this issue, it can be seen that there would be room for improvement in this regard so as to tackle this challenge more effectively.

- **Lack of applicability of statistical data of manned aircraft:** this issue is related to the specific methodologies employed within the different disciplines, so it is not directly seen at the level of granularity of the trend analysis in subsection 4.5.2. However, some comments were already made in this regard for the overall field of RPA design within the review of chapter 2, where it was seen that the area of statistical estimations has seen a noteworthy interest. In spite of this, specific gaps were detected in this area, with no trends being available for certain variables such as those of the tail surfaces. These findings have been complemented with the information which has been found for RPA design environments of these aircraft, where two main approaches have been seen. The first one involves skipping the use of empirical approaches to move directly on to higher fidelity approaches and optimisation, neglecting the initial sizing and even the overall conceptual design stage. The second consists in employing empirical relationships and trends of manned aircraft to fill in this gap. Both approaches have particular shortcomings which are further discussed below.
- **Implementation of regulatory requirements in the design process:** as seen in detail through chapter 3, it has only been recently when the regulatory paradigm of RPAS has started to consolidate, and it still constitutes a very dynamic field with many changes in the regulations and rulemaking tasks ongoing. This can explain why airworthiness matters have seldom been considered in existing RPAS design environments, and where they have, regulations from manned aircraft have been employed as mentioned in subsection 4.5.2. Nevertheless, the gap in including the already available airworthiness standards within these environments would remain, and it can potentially constitute a noteworthy prospect to see how these regulations affect the design space of RPAS in their initial stages.
- **Configuration diversity and widespread use of atypical layouts:** this aspect links with the trend of unconventional layouts and its conclusions as discussed in subsection 4.5.3, where it was seen that a larger effort on configurations different to the tailless one would constitute a noteworthy line of future work. Furthermore, in the case of RPAS an additional issue appears as already commented in subsection 4.5.2, which is that there is a mismatch between the types of layouts which can be analysed by current environments, as provided in Figure 4-12, and the most widespread configurations employed in existing RPAS designs, with the H-tail being more common than conventional and T-tail aircraft and the V-tail layout being as usual as the conventional one. These trends shall be substantiated through the statistical results of chapter 7 of this thesis. With respect to tail surface definition in conceptual design, this was already emphasised in section 2.2 as a fundamental part of the overall initial sizing process, which currently showed a gap in statistical approaches when compared to manned aeroplane methodologies, with this being a shortcoming also detected in current design environments for these aircraft. Thereby, further work in developing and

implementing sizing methodologies adapted for these configurations would be required to make current environments more aligned with the design options more commonly used in existing RPAS.

- **Overall lack of applicable conceptual design methodologies:** this challenge is connected to many of the previous ones. As mentioned in 4.5.2, most of the environments are mostly focused on manned aircraft, with those covering both aircraft types tending to prioritise the conventionally-piloted ones. Thereby, it has been seen that in some cases design approaches for manned aircraft, even those based on empirical relationships, are employed for RPA design, which is in contrast to comments given by other authors with respect to the need for careful tailoring of methodologies to ensure their applicability to RPA. As it has been discussed beforehand both in chapter 2 and also in subsection 4.5.2, this trend of reusing existing methods could be explained when considering the heightened effort that could be required to both develop novel methodological design approaches, and then to implement them in design environments. Since the current landscape of design methods themselves for RPA shows various gaps as analysed in chapter 2, the developers of design packages might tend to resort to existing approaches available for manned aircraft, in spite of potential applicability concerns. This might also explain the heightened emphasis on higher fidelity methods for RPA design as mentioned beforehand, since applicability issues might be mitigated due to the models employed by these approaches, but once again it results in neglecting the conceptual design stage.

From the assessment provided above for each of the challenges, it can be seen that current design environments for RPAS would yet present relevant gaps towards fully addressing the main hurdles related to the conceptual design of these aircraft. One of the main points highlighted above relates to the ways in which current gaps in the overall realm of RPAS design affect the specific area of design packages. In particular, as seen in the review of chapter 2, there is a significant lack of methodologies in several topical areas related to RPA design approaches at a conceptual level, with relevant gaps also being present in existing methods. Furthermore, as also expounded in section 2.3, it was seen that there are relevant connections between different topical areas, with some having a broader scope than others. The approaches at a coarser level of granularity were usually constructed from smaller building blocks related to methods with a more specific scope (such as those focused on matching diagram, integral performance, and so on). Therefore, it is required that methodologies are available at the finer level of granularity so that those at a coarser level can then be developed.

Considering the above, and going back to the topic of this chapter, which is that of computerised environments, the developer of design packages for RPA is faced with a significant issue: which methodologies should be implemented in the environment, considering that there are few generalisable design approaches available at a conceptual

level within some of the most relevant topical areas? As seen in chapter 2, design environments are usually constructed through the implementation of methodologies at finer granularity levels, where there are significant gaps in the field of RPAS, particularly in those of the GDM type, which are the most generaliseable. This is also why both in subsections 4.4.6 and 4.4.7 it was stated that the first step towards the development of design environments covering unconventional vehicle and RPA design is the development of novel design methodologies themselves at a conceptual level, so as to cover the gaps at the finer granularity level and then implement these approaches within the design environment. This reinforces the connections among the different topics covered in the thesis as already introduced in section 2.3.

However, and as commented beforehand, a significant effort would be required to both develop novel design methodologies, and then to program the design environment and implement the aforementioned procedures within it. This may be the reason why many works focusing on design environment development are mainly concerned with implementing already existing methods, placing the emphasis on the suite itself. Albeit this is not a problem in the realm of manned aeroplanes due to the mature and widespread range of methodologies available, it can be an issue within the field of RPAS where there are many gaps in the design procedures themselves as seen in chapter 2. Therefore, two main approaches have been used by design packages showcasing functionalities related to RPAS design in this regard, which are, as mentioned beforehand in the list of challenges, either to reuse manned aeroplane design methods, or to skip the initial stages of design and focus on higher fidelity approaches.

The fact that many procedures implemented in design packages for the development for RPA have reused manned aeroplane approaches has been highlighted in previous research (18). As mentioned through the thesis, and as also commented by previous authors in the field, this approach can potentially yield inaccurate results if careful adaptations are not considered. However, and particularly in design environments that cover both manned and unmanned aircraft design, this has been seen in various cases, as commented in 4.5.2. These applicability concerns depend on the type of methodology, and they have been considered more pressing in the use of statistical relationships and certain semi-empirical methodologies, but may also apply to other physics- based approaches. For instance, and as mentioned in section 1.3, viscous drag estimation approaches for the drag polar have been noted to require adaptations for RPA (52; 53), whereas vortex-lattice approaches such as AVL to estimate vortex drag have given excellent results as demonstrated in (70). However, many current design environments for RPAS use empirical mass estimation procedures and other statistical approaches which have been derived from manned aircraft. Thereby, new rapid methods would have to be developed first so as to allow their implementation in computerised environments to substitute the direct use of manned aeroplane methodologies towards ensuring the applicability and accuracy of the results.

The second approach involves the use of higher fidelity methods, which might be more generalisable to unconventional layouts and RPAS. This viewpoint was already been expounded in detail through subsections 4.4.5 and 4.4.6. It constitutes an inviting avenue for packages covering both the design of manned and unmanned aircraft, as it allows to leverage the same methodology for the different aircraft types. This approach is remarkably well-suited for the advanced stages of the design continuum, where small variations on previously defined configurations are studied with a high level of detail, usually within an optimisation framework. However, the exclusive use of these approaches would leave the particular needs of the conceptual design stage unattended. As commented in subsection 2.1.2, the impact of this phase on the overall design process is noteworthy. In spite of this, as seen in the trend analysis of subsection 4.5.2, even within most comprehensive design environments, the process of RPAS initial sizing is not usually carried out, or if it is present it may skip certain key steps. This is consistent with the lack of overall initial sizing methodologies for RPA as seen in the survey of chapter 2.

As a result, many design environment functionality areas for RPA design require as an input an initial definition of the geometry of the vehicle. This is in contrast with the usual conceptual design approach, which starts from the requirements, with the initial sizing step then providing potential definitions of the geometry as obtained from a methodological process. The fact that the initial layout and its dimensions need to be pre-defined in many RPA environments could result in a lack of efficiency of the optimisation process, as a wider design space has not been explored beforehand through rapid methods to hone in the most promising concepts. Therefore, the most promising solution would be to leverage both kinds of approaches in the same framework, which could be achieved by developing novel initial sizing procedures for RPAS to cover the first step of geometry definition which is nowadays yet not addressed in a methodological manner. This combined use of rapid and higher fidelity approaches fits with some of the viewpoints mentioned when expounding the multi-fidelity perspective as developed in subsection 4.4.5, with previous works in the field of design packages having already emphasised the advantages of implementing in these suites rapid methodologies for rapid design space exploration (59; 100). As a matter of fact, it has also been previously seen that previous works have also shown significant interest in the development of rapid methods for the conceptual design of unconventional layouts and RPA (58; 60; 259) and also in their implementation within design environments (18; 70).

In view of the above, a greater emphasis on developing conceptual design methodologies for RPA is not only fundamental towards addressing the gaps within the overall realm of RPA design as seen in chapter 2, but also the availability of such approaches would constitute a key enabler towards the development of computerised environments that can cover this design phase, which as seen through this subsection, is also one of the gaps of this field. Giving a higher attention to the initial sizing steps would also allow to enhance current comprehensive design environments and to develop new ones specific for RPAS design. However, as analysed through chapter 2, since such methodologies are currently

not available in various topical areas, or they present relevant gaps, their development would constitute a first hurdle which would have to be surmounted to enable the development of design environments covering the initial sizing of RPAS. Therefore, when planning the development of a computerised environment for the conceptual these aircraft, it would be crucial to first see whether currently available methodologies might cover its needs, or if not, to consider the initial effort which would be required to develop them before their implementation can be enabled.

Therefore, in spite of the overall availability of a certain number of environments covering design tasks for RPAS, the current state of these frameworks in terms of tackling the challenges required to address the initial sizing steps of these aircraft would still require future improvements so that the hurdles listed above may be surmounted through the use of these design packages. Gaps have been detected in various areas which are key to address the challenges for RPA conceptual design as laid out in section 1.3. These include: the relative lack of specific methodologies tailored for RPA, the need for improvement in initial sizing methodologies, a larger emphasis on certain atypical layouts such as the H-tail and the V-tail which are commonly used in RPA, the fact that the medium size RPA category has not received as much attention in spite of its ubiquity in existing and deployed aircraft, and the need to integrate certification considerations, among other points.

Some of the existing environments have placed a higher emphasis on the conceptual design stage, and they have also highlighted to a greater extent the need of developing new design approaches for RPAS. These viewpoints have been seen most frequently on those packages which have been specifically developed for these aircraft. However, there are still some potential avenues of improvement in these environments. The suite developed in the work of (70), which has been developed mainly for educational use in the setting of university capstone project, places emphasis on rapid methodologies to explore an expansive design phase, and includes the option of developing configurations with diverse tail layouts. However, it is only focused on small RPA, and certain components of the aircraft seem to be given directly as an input by the user, instead of following a programmed methodological process to size their dimensions. The package developed in (17) is mainly focused on the conceptual design stage and can perform the sizing of aircraft with revolutionary powerplant architectures, but it does not include the most usual layouts and powerplants which are seen in most existing RPA. The design environment described in (137) allows to compare different layouts options and includes various disciplinary modules, but the methodologies for initial sizing are not described in the reference, and it mostly seems to be focused on a particular SAR mission. In none of the cases have multi-role sizing capabilities been demonstrated in the conceptual design stage, nor have airworthiness requirements specific of RPA been explicitly considered.

Finally, and aside from the gaps mentioned beforehand, there is also another hurdle which would impede the use of the existing environments to tackle the main research objectives

of this thesis, which is the fact that they are proprietary. As commented beforehand, this is a common characteristic of most design environments which has already been remarked in previous research to constitute a significant hurdle for further development in this area (18), as it means that they cannot be readably reused, nor can their source code be accessed. Furthermore, the related publications which have been consulted within the state-of-the-art often do not give detailed information on the methods and models which have been implemented in the environment. This issue has not only affected the review process of this chapter, but it also complicates evaluating certain aspects of existing packages, and it also means that the methods cannot be checked or implemented by other users. As a result, within the context of this thesis, the methods of existing design environments cannot be reused or tested, so new design methodologies must be developed.

With all of the above, it can be seen that there would still be room for improvement in terms of RPAS design environments for conceptual design, both considering the overall trends and some specific cases which are closer to this design stage. Therefore, it can be concluded that the tools which are currently available would not allow to address the main objectives of the thesis in terms of surmounting current RPA conceptual design challenges. Advancements would be required both in the methodologies to be implemented within the packages, as well as in the environments themselves, so that the present shortcomings can be tackled and the main hurdles towards RPA initial sizing can be surmounted.

4.6.2. Key areas of work towards the development of future initial sizing RPA design environments

In view of the results of the previous assessment, it is seen that there is still room for improvement in the current landscape of RPA design environments towards their use in the conceptual design of these aircraft. To further advance in this area, as mentioned above, improvements would be required both in terms of the available design methodologies, as it was seen in chapter 2 that there are relevant gaps in this area; and also in the development of the design packages themselves.

As it was commented beforehand, the first task would precede the second, since the methodologies would have to be available before their implementation. This first area of work shall be tackled in detail within part III of the thesis, where the objective of developing novel design methods will be addressed as part of the tasks related to OBJ.3 of this thesis. However, aside from this, and considering the potential of computerised environments as seen through this chapter, it is also sought to propose here some guidelines towards the development of future packages which could aid to address to a greater extent the challenges for the conceptual design of RPA which were seen in section 1.3. Albeit some of the lines of work to be proposed here shall be shared with those aspects related to the scope and capabilities of the design methodologies themselves, others will focus to a

greater extent on the overall features of the environment. Within the context of this thesis, and following the relationships among the different granularity levels and topics that are covered within it as expounded in section 2.3 and illustrated in Figure 2-6, the guiding criteria to be proposed here shall also have an influence on the design methodologies to be developed within part III. The purpose is that these novel design methods do not only cover the requirements established for each of them, but also that they are developed in such a way that they are aligned with particular considerations related to design environments, in case that in the future they are implemented within a prospective design package for RPAS.

The guidelines proposed here towards the research in new conceptual design environments for RPAS are based on both the particularities of these aircraft when compared to conventionally-piloted ones, and also on the gaps that were discussed in the previous subsection. They have mainly been devised thinking about environments to be developed specifically for RPAS, as in view of the survey and analyses conducted beforehand, these are usually the ones that consider to a larger extent the peculiarities and singular needs of RPAS, thus they tend to be more aligned with addressing the challenges of this field. However, these guidelines could also be applied to design packages covering both manned and unmanned aircraft types. The ten lines of research which have been identified would be the following:

- 1) **Emphasis on different RPAS size categories:** up until now in current design environments, the focus has been mostly on small RPAS, with those in the medium and large ranges being comparatively neglected. However, medium RPAS such as those in the tactical range, are also extensively deployment, and in contrast they are only covered in two functionality areas. Therefore, it would be desirable that the design package can cover these various types of RPAS
- 2) **Design capabilities for a broad range of layouts:** as mentioned through this thesis, RPAS present a wide variety of configurations, and they tend to employ layouts which are considered unconventional in manned aeroplanes. As mentioned beforehand in 2.3, the previous review of (21) supports that the consideration of the different layouts of RPAS is one of the two essential points towards addressing the design challenges of these aircraft. Particularly, it would be key that the environment would present capabilities related to conventional, T-tail, V-tail, and H-tail sizing, which are the most usual layouts in RPAS as it will be seen in chapter 7 of this thesis. This could be achieved either through the development of methods particular to each layout, or either via approaches that are generalisable to all of them. In particular, rapid sizing approaches to perform a first estimation of the main variables associated with these components would constitute a noteworthy advancement in view of current gaps in the state-of-the-art. Furthermore, the possibility of conducting trade studies would be crucial to

aid the designer in performing an informed selection of the best candidates among potential configurations, as proposed previously in (17).

- 3) **Focus on electric and/or reciprocating powerplants:** as seen in previous studies, these are the most usual ones in RPAS (36; 39). These are currently considered in various design environment functionality areas for RPAS. However, perhaps a greater emphasis on reciprocating engines would be desirable, since in the realm of already existing and deployed RPAS designs, the ones with these engines tend to double those with electric motors.
- 4) **Adaptation of design methodologies or development of new ones:** as it was seen beforehand, some existing design environments for RPA reuse design approaches for manned aircraft. This can result in potential applicability and accuracy concerns, specially when dealing with statistical or semi-empirical approaches. Thus, it would be recommended that the envisioned design packages for RPAS either implement existing methods which have already performed adaptations or developed new approaches for these aircraft, for instance through the reuse of procedures proposed in the references compiled in the review of 2.2.4, or even that new design procedures are first developed within the scope of the envisioned design environment before moving on to the implementation stage. This larger reuse of existing methodological approaches and the creation of novel ones fits with the second essential point laid out by the review of (21) towards addressing the challenges of RPAS design as expounded in section 2.3.
- 5) **Types of design approaches and modules included:** it can be seen from Figure 4-15 that the disciplines of aerodynamics, propulsion, mission/performance, and mass estimation constitute the four main cornerstones of design environments both for manned and unmanned aircraft. This also fits with the disciplines which would be required to complete a design loop covering the overall initial sizing step as commented in subsection 2.2.3, so they would be required for most conceptual approaches and should be considered for design environments of RPAS covering this stage. However, as seen in the review of chapter 2, and as also commented through this chapter, there are some specific gaps in each of these areas within the current landscape of RPAS design, which should ideally be covered before they are implemented in the design environment.
- 6) **Mission definition flexibility and multi-role capabilities:** connecting with the above point, it was seen both in chapter 2 as well as in the present one that there is a gap in conceptual design approaches for multi-role RPAS which can size the aircraft attending to multiple missions at once. This is one of the main challenges in the area of RPAS design, so advancements in this line of work could constitute a promising prospect. Even though mission and performance modules are widespread in state-of-the-art environments as mentioned above these would

have to implement a greater degree of flexibility in mission definition so as to encompass the multiplicity of activities for which RPA can be deployed.

- 7) **Consideration of airworthiness requirements:** as seen from the regulatory survey conducted in chapter 3, specific regulations for RPAS have already been published, so considering these regulatory requirements which are currently in place would be desirable. Aside from covering one of the main gaps in the overall area of RPAS design, this could allow the designer to evaluate, through the use of the package, how the design space is affected by the applicable regulations, and it would constitute a significant novelty with respect to existing design environments. However, a relevant consideration would be that the integration of airworthiness requirements in the design process should be flexible, as there are many different applicable regulations depending on the characteristics of the RPA and the regulatory paradigm being considered (EASA, FAA, NATO, etc.). Furthermore, due to the current dynamism of this area of the regulations, and so as to avoid the airworthiness module of the package from becoming obsolete if there is an update, it would be desirable that the airworthiness restrictions to be employed are easily accessible, for instance through a central airworthiness module or database, so that they can be managed and modified, thus updating all related considerations through the environment.
- 8) **Method flexibility:** this capability is already present to a certain extent in the overall field of design environments, but as seen in Figure 4-14 it is not yet as common for those specific of RPAS. Aside from allowing to model a variety of missions as mentioned beforehand, other flexibility aspects would be worth considering. Connecting with the consideration of a broad range of layouts mentioned above, model adaptations depending on the configuration which is being considered would be required to allow that capability, thus involving a certain degree of flexibility. This would also apply to the airworthiness considerations as mentioned above.
- 9) **Modularity and workflow flexibility:** as seen in Figure 4-14, this capability still shows room for improvement, particularly in functionality areas related to RPA. Taking into account the remarkable diversity of RPAS applications (35), the needs of each design case might require for the use of different models and tools (17). In combination with the aforementioned method flexibility, the organisation of the environments and methods following a modular approach, and the possibility of combining them in different ways to establish design workflows according to the needs of each project, could constitute a remarkable aid to allow the design environment to adapt to the different application cases faced by the designer.
- 10) **Development of new common data models:** these KBE-related approaches could constitute a fundamental asset for future design environments for RPAS, as they do not only provide advantages of their own, but also aid in several prospects

such as interoperability and extensibility. Albeit there is currently a data model compatible with these aircraft, it is only used within a proprietary package. The flexibility and extensibility advantages that a common data model could provide would be extraordinarily beneficial taking into account the dynamism of this field, which can require future updates and expansions of the capabilities of the environments. This does not only apply to airworthiness regulations as mentioned beforehand, but also to the research in novel methodologies and tools for RPA design. The common data representation could allow the models and the package as a whole to be updated more easily, and would also allow for seamless connection with external analysis software, which may be particularly relevant along time as the area of RPAS analysis and design further matures and a greater number of specialised tools becomes available. Furthermore, new approaches for data modelling with additional advantages could be investigated, such as knowledge representations based on Web technologies, as it will be seen in the following chapter of the thesis.

It can be seen that many of these guidelines are also related to the gaps identified within the broader review of chapter 2, and some are also aligned with key areas of future research as laid out in previous works within the broader RPAS design field (21; 33). Furthermore, they also seek to answer some of the current shortcomings seen both in the overall trends of the field of design environments as well as those specific to RPAS. Albeit these areas of work are mainly focused on environments envisioned for the conceptual design stage, since this is also the scope of the thesis, many could also be applied for comprehensive environments covering various design stages, as in any case the conceptual design phase would have to be implemented to truly provide a holistic design process within the suite to be developed.

In view of the guidelines proposed above for the development of future design environments for RPAS, it is seen that it would be required to advance in both main areas of interest of this field of design packages as laid out in 4.4.1: that of design methodologies themselves, and the one on software and overall capabilities of the environment. Both are present through the future lines of work suggested in this subsection, which is also substantiated due to them being strongly linked together as seen in 4.5.1. Some of the lines of research proposed above shall be further developed in chapter 6, as they will have a direct influence on the novel design methodologies to be developed in this thesis. With this, it is sought to achieve that the new approaches to be developed in part III of the thesis do not only aid in advancing the overall field of RPAS design, but also the specific area of computerised environments for these aircraft.

4.7. Summary and conclusions

The area of computerised environments is among the most dynamic ones within the broader realm of aeroplane design. In recent times, an outstanding research effort is being invested in this field, mainly due to the remarkable promises that these programs show in terms of addressing the main current challenges of aeroplane design, as they aid the designer to manage the growing complexity of both the aircraft concepts being developed as well as that of the design tasks themselves.

Considering the hurdles that RPA design is presently facing as seen beforehand within this thesis, the ultimate objective of this chapter has been to assess whether the currently available suites could aid in tackling the present challenges of RPA conceptual design as laid out in 1.3, and thus if the existing tools could be employed within the context of the overall objectives of this thesis. In order to achieve this, it was first required to scrutinise the state-of-the-art of existing aircraft design environments, so as to detect the main trends and challenges that represent the foremost areas of research in this field. Then, in view of these main lines of work, the current capabilities of existing environments were evaluated. This then allowed to see whether the features of current suites are aligned with those which are required to tackle the main challenges of RPA conceptual design. These three steps resulted in the formulation of the specific objectives of the investigation of the chapter, with each being carried out in sections 4.4, 4.5, and 4.6 respectively, and with all leading to the accomplishment of OBJ.2.2 of the thesis as a whole. The main findings from each of the aforementioned objectives are summarised below:

- 1) With respect to the **analysis of current trends**, seven main lines of work were identified from the common concerns of current developers of design environments. Each of them was expounded in the different subsections of 4.4, analysing both the drivers behind the interest in each of them, the current approaches being employed in these fields, as well as the advantages that they can contribute to design environments. Precisely the development of design environments for RPAS was one of these seven areas of research. It was seen that some of these trends were mostly related to the capabilities of the design methodologies implemented on the packages, whereas others were more tightly connected to software engineering aspects and overall package capabilities. These correspond to two main areas of interest in this field as laid out in 4.1.1, and it was seen that they are tightly coupled, with advancements in one aiding in the capabilities of the other.
- 2) Regarding the **evaluation of features of current design environments**, several characteristics related to the previous trends were defined. Upon analysing a representative set of packages, it was seen that there is currently a dissimilar scenario among the distinct areas of work of the previous section, with some such as interoperability or method flexibility showing a wide level of implementation, whereas others such as collaborative environment design were only seen in a few

environments. Moreover, it was seen that the characteristics of manned and unmanned environments were remarkably different in some cases, such as in method flexibility, or in the powerplants analysed by the methodologies in each case. Furthermore, it was seen that there were remarkable differences between RPAS-related capabilities between those environments specifically tailored for these aircraft, and those which covered both manned and unmanned aircraft design, with the first ones usually being more tailored to the specific needs of RPAS. Overall, a higher emphasis on preliminary design rather than on conceptual design was detected, which coincides with observations from previous authors.

- 3) In terms of the **assessment of current suites towards the design of RPAS**, it was seen that there is still room for improvement in this regard. Albeit current environments, particularly those specifically tailored for RPAS, show a noteworthy set of capabilities, most environments have been developed mainly with the issues related to manned aeroplane design in mind, so further work would be required to ensure that all current challenges of RPAS conceptual design are addressed. Thereby, ten lines of work were proposed in view of the present gaps and the ways in which additional features could aid to surmount them.

As seen in the ten lines of future work towards the development of new conceptual design environments for RPAS, both of the two main areas of interest within the field design packages mentioned above appear through many of these points. This was anticipated within section 4.1 and in Figure 4-1, where they were proposed among the overall considerations to be taken into account through the chapter. Both of them present notable connections to each other, so advancements in these two areas would be vital to enable future environments to cover all design challenges of RPA.

With respect to the first area, that of the design methodologies themselves, as seen before in Figure 2-4 within chapter 2, the core of design packages is primarily fed from design methods, so these are essential elements to constitute and implement the envisioned design packages. Thereby, the development of novel design approaches themselves constitutes a key area towards the improvement of the capabilities of current design environments. The gaps in design procedures seen both within chapter 2 and in the ten points laid out in 4.6.2 related to this aspects mostly match, which is to be expected, as if shortcomings are present within design methodologies, these issues shall also be present in the design environments in which they are implemented.

A very remarkable case is that of initial sizing methodologies, which are nowadays lacking particularly in the area of RPAS design, which could also be anticipated in view of the small array of available methods in this regard within the broader field of RPAS design. This topical area is crucial to obtain an initial definition of the aircraft from the Top Level Requirements (TLRs), even aiding the designer in selecting the most promising configuration. In contrast, most current approaches implemented in design environments either skip certain steps of the initial sizing process, or even start their analyses from an

already defined geometry given by the user, which is not obtained from a methodological processes implemented in the environment. This gap was also seen in the survey of chapter 2, and considering the impact that the conceptual design stage has in the overall aircraft development process, addressing it would constitute a noteworthy advancement.

At the same time, the development of initial sizing approaches also requires advancements in filling the gaps of particular areas of each discipline involved in this design step, which was also seen in the schema of the connections among topical areas illustrated in Figure 2-4. These include, for instance, the consideration of the multi-mission capabilities of RPAS in performance methods, and the development of novel statistical approaches. Therefore, to achieve further advancements in computerised environments, it is first required to address the gaps in the topics pertaining to lower granularity levels. In view of the gaps seen both through this chapter and those of chapter 2, this task will be tackled as part of OBJ.3 of this thesis starting on chapter 6, where the ten lines of future research in computerised environments for RPAS that were identified here shall have a vital influence in the research directions to be decided for the particular design methodologies themselves. With this, a further step is taken in the process of relating the needs and requirements from the topics at a coarser granularity level on to those at finer levels, as laid out in sections 2.3 and 2.4, therefore advancing in the overall research flow of the thesis, and constituting a key link between this chapter with part III of the thesis.

Aside from advancing in the capabilities of the available design methodologies themselves, it would then be required to integrate them within the computer program. When conducting this step and also when assembling the full design package as a whole, the second main area of interest of the field of design environments is key, with this area being related to the computational capabilities of the software. As it has been seen through the trend analysis conducted in 4.4, the topics related to this second area are strongly linked to subjects such as software engineering, knowledge representation, and distributed computing, among others. As mentioned through this chapter, the two main areas of interest within design environments show remarkable synergies, so advancements in both of them are necessary, with improvements in computational and software engineering aspects easing some of the design-related challenges which are currently being faced by this software. Therefore, this second area should not be neglected, as it has even been seen that the topics related to it have experienced a very noticeable increase in research output within recent times.

In spite of the above, there is also room for future research in aspects related to this second area, and even more so in the realm of RPAS design environments. Common data models for information exchange which have been particularly tailored for the design tasks related to these aircraft are still scarce, and none are yet available in the public domain. As seen in Figure 4-8, these data formats can act, either directly or indirectly, as enablers to many of the other six challenges. Furthermore, it was seen through section 4.4 that the study on Web-based technologies constitutes a promising area to enhance

aspects related to some of the trends studied there, not only the one related to KBE, but also those of interoperability and collaborative design. With all of this, considering the relationship of the field of KBE with that of AI, and also taking into account the promising prospects of AI-based design approaches for RPA as seen in chapter 2, further research in this area could contribute to enhance both design methods for these aircraft as a whole, as well as to enhance many aspects related to computerised design environments. As mentioned beforehand, the AIDA design environment, which is heavily based on AI methods, already constitutes a promising precedent in this regard.

This sets up the scenario to study the possible use of AI-related techniques in the area of computerised design environments, which shall be one of the main lines covered within chapter 5, which is the one dedicated to the intersection of AI with other main topics of the thesis. Considering the particular needs of the field of aviation with respect to AI, and also other specific aspects related to the current landscape of design environments, the potential advantages of the use of ontologies (which are semantic artifacts used to represent knowledge and which can be employed in the context of symbolic AI approaches) in this area shall be studied in detail, proposing avenues of application and analysing how they can improve the current techniques used in computerised environments within various of the aforementioned trends. This matter shall be developed in full detail within chapter 5, and it constitutes another way in which the findings of the present chapter influence other lines of research of the thesis.

Overall, the study of computerised environments developed within this chapter has proven to be decisive in the context of the overall thesis in terms of its influence in other lines of research. Aside from this, this field constitutes a remarkable area of research on its own, and the analyses conducted in this chapter have sought to offer new perspectives and insights which were not covered in previous works. This is due to most references in this field having focused in the development of their own design packages, with few studies offering a broad overview of the field and an analysis of its main trends, capabilities, and possible future research directions, particularly in the specific area of RPAS. Therefore, the studies developed in this chapter have sought to cover these aspects within the research context of the thesis and focusing on its main objectives. Certainly, there are many other avenues of potential research in this field, such as the improvement of preliminary and detailed design methodologies, and certain software-related aspects such as advancements in integration frameworks for distributed design. However, these would fall outside the scope of this thesis. Nevertheless, in view of the dynamism and potential of the field of computerised environments, it can be expected that along the following years this area shall continue attracting a noteworthy research effort resulting in further breakthroughs directed towards further improving the tools available to the aircraft designer to tackle ever more complex design endeavours.

5. SELECTED TOPICS OF ARTIFICIAL INTELLIGENCE RELATED TO RPA DESIGN

Artificial Intelligence is presently one of the most revolutionary areas in science and technology, opening a wide array of new possibilities and challenges. This is also the case in the field of aviation, and particularly in the areas of aircraft and RPA regulations and design, which are core topics of this thesis. The remarkable interest of AI developments and applications in these areas has led to its consideration as one of the three outstanding topical areas to be investigated in part II of the thesis, as outlined in the introduction.

The subject of AI in aviation, even in the more delimited areas mentioned above, is an extraordinarily expansive topic, covering many possible AI techniques, approaches, and applications. The purpose of this chapter is not to conduct a detailed study of the full extent of the possibilities of AI in aircraft and RPA design. Rather, the focus shall be on some specific topics related to AI which are strongly linked with other subjects addressed within the content of this thesis, as formulated in OBJ.2.3. In particular, as it will be substantiated through section 5.1 of this chapter, two main areas of effort in AI developments have been identified in the state-of-the-art which strongly link with nuclear topics of the thesis:

- 1) Development of regulatory material to ensure the safe integration of AI technologies in aviation applications.
- 2) Use of AI to enhance manned aircraft and RPA design processes, models and tools.

Each of these two areas shall be studied in detail within this chapter, seeking to deliver an analysis of their present status in terms of research and development, so as to then provide original insights on the potential connections and opportunities of each of them in relation to the topics of the thesis. Thus, contributions of both the RCT.1 and RCT.2 types will be developed through this chapter, allowing to enrich the central topics of the thesis with the perspectives and opportunities of AI.

In the case of the first area, an overview of the current efforts from various Aviation Authorities in the development of guidance material for the use of AI within aviation shall be conducted. From these findings, and recovering the thread of the review on airworthiness standards for RPA conducted on chapter 3, an investigation is conducted on the prospective connections between RPA regulations with the main areas of interest in AI rulemaking. For the second area, taking into account the findings from chapter 2 in relation to the potential uses of AI for RPA design, and also in view of the current trends and possible areas of improvement in computerised environments as seen in chapter 4, the prospective use of AI to enhance aeroplane and RPA design packages will be investigated. Considering the wide variety and characteristics of the different AI models, a particular approach related to AI will be selected to study in more depth its

opportunities and challenges within this area. As it will be substantiated later on in this chapter, the selected subject has been that of ontologies, which are a knowledge representation paradigm that allows to formalise vocabularies of terms and the relationships between them. When implemented in knowledge representation languages containing explicit semantics, these representations can be employed by various KBS and AI approaches.

The contents of this chapter are structured as follows. In section 5.1, a theoretical background is provided on AI concepts which will be essential towards future decisions and discussions taken along the chapter. This section also includes an overview on the criticality of safety assurance when studying possible AI applications within the aviation domain, which is another consideration that permeates the investigation developed in this chapter. In view of this background overview, the two main lines of work to be developed within this chapter shall be substantiated. Then, section 5.2 develops the research on the link between AI and RPA regulations, and section 5.3 undertakes the investigation of potential applications of ontologies in aeroplane computerised design environments. Finally, a set on closing remarks shall be provided in section 5.4 on the central topics of this chapter, on their connections with the other chapters and findings of the thesis, and also on other potential AI-related endeavours in relation to RPA design.

5.1. Introduction to AI concepts and safety implications in aviation

This section provides an introduction to the AI-related topics covered in this chapter, as well as the safety implications that necessarily arise when considering the use of AI in aviation. It serves to lay out the fundamental concepts and background which are the basis for the investigations, decisions, and discussions conducted later on, including the reasons for selecting the particular lines of research on AI that are prioritised in this chapter, which are AI regulations and ontologies.

The first subsection gives a thorough introduction to the field of AI, and develops the characteristics of the main two categories of models considered here: symbolic and subsymbolic AI. As it will be seen, the approaches, characteristics, and even safety implications of both of these types of AI show remarkable differences. This is among the main reasons for conducting this detailed background review, since their characteristics shall be key in the remainder of the research of this chapter. The second subsection provides an overview on the interest of AI applications within the realm of aviation and substantiates the criticality of considering AI safety implications when seeking to integrate AI models in this domain. Finally, in view of this background, the last subsection provides a more detailed rationale for the selection of the two main lines of research that are developed in the remainder of the chapter.

5.1.1. Definition of AI and classification of techniques

Here, a theoretical background is provided on the definition of AI, as well as an overview of the classification of AI techniques and the main characteristics of each of the two groups considered in this work: symbolic AI and subsymbolic AI. These concepts are an essential foundation for the following decisions regarding the research directions within this part of the thesis, as well as towards the investigations themselves and discussions present through this chapter.

(a) Definition of Artificial Intelligence (AI) and intelligent agents

There are many different definitions of Artificial Intelligence in the open literature, each emphasising distinct notions and presenting subtleties in comparison with others. Here, two of them are considered.

From the core field of AI, Russel and Norvig's definition of AI is: *"The designing and building of intelligent agents that receive percepts from the environment and take actions that affect that environment"* (233). The definition of an agent is: *"anything that can be viewed as perceiving its environment through sensors and acting upon that environment through effectors"* (233). It should be noted that the environment can be a virtual one, such as in the case of a computer program that performs simulations, in which case the percepts and actions would be encoded bit strings. Furthermore, an ideal intelligent agent is defined as that one which: *"for each possible percept sequence, an ideal rational agent should do whatever action is expected to maximize its performance measure, on the basis of the evidence provided by the percept sequence and whatever built-in knowledge the agent has"* (233). It is seen that agents have certain goals which they seek to accomplish in an optimal manner. Another key point of the definition is that agents have certain implemented knowledge, which is fundamental in their design, as recognised by the authors, since it allows the agents to make better decisions regarding their actions (233). The agent can also gain new knowledge through a learning process. These concepts of knowledge and learning are key to the development of this chapter, and will be further discussed below.

On the other hand, a definition pertaining to the intersection between AI and aviation is included here, which is that of the EU AI Act (268), adopted by EASA in its AI Roadmap (65). It establishes that an AI system: *"means a machine-based system that is designed to operate with varying levels of autonomy and that may exhibit adaptiveness after deployment, and that, for explicit or implicit objectives, infers, from the input it receives, how to generate outputs such as predictions, content, recommendations, or decisions that can influence physical or virtual environments"* (268). Parallels can be drawn with the previous definition of AI pertaining to the design of agents. Here, the concepts of the AI being machine-based, and its capacity of learning, are emphasised.

Within the context of this thesis, an intelligent agent could be, for example, a computer system which examines the current state of definition of the aircraft at different stages of

the design process, and recommends to the designer possible next synthesis methods to apply in order to leverage the currently available information so as to perform more advanced analyses and further define or refine the aircraft concept. This system could also select, in view of the information available of the aircraft concept and the design phase of interest, the appropriate analysis or synthesis methods attending to the inputs required, the desired outputs, and the objective level of fidelity.

A collection of other AI definitions can be found in (269), containing both those with a broad applicability scope, such as the ones presented above, and also those pertaining to particular subdomains.

(b) Knowledge and learning of intelligent agents

As commented beforehand, an essential component of intelligent agents is knowledge, which is a fundamental asset for them towards achieving their objectives. Furthermore, intelligent agents usually have some form of learning process, which is the capability to deduce new knowledge, aside from that which has been pre-programmed in them. Both knowledge representation and learning constitute key factors towards intelligent agent design, and it is reasonable that agents have both a set of initial knowledge as well as certain ability to learn new knowledge (233).

Knowledge can be of many different types: facts, models, distinctions, relationships, constraints, procedures, heuristics, etc (270). With the purpose of organising these knowledge types, various distinctions of knowledge have been proposed, with each of them performing a classification of knowledge following different criteria. For instance, one distinction would be between procedural or declarative knowledge, and another would be among domain-independent and domain-specific knowledge (270). The kind of knowledge that is intended to be used by an agent has a direct impact on the most appropriate way of knowledge representation. In any case, this knowledge has to be formalised and implemented within an intelligent agent in a way that a computer can make operations with it: that is, it must be codified in a machine-readable format, so that the agent may employ it. Therefore, the topics of knowledge representation and formalisation is an essential part of the field of AI. A more thorough exposition on different types of knowledge, classifications and distinctions of knowledge, and their relationship with representation techniques, can be found in references (270) and (226).

Knowledge representation is one of the main areas of interest of the discipline of Knowledge Engineering (KE), also often called Knowledge Based Engineering (KBE), which is itself tightly linked with the field of AI (226; 271; 227). The topic of KE was already introduced in subsection 4.4.1, where it was seen that KBE-related capabilities were one of the seven main trends within aircraft computerised environments. At that point, an overview was provided of the main objectives of the techniques employed within this field, along with the advantages that can result from their application, with a special emphasis on the areas of aerospace engineering and design, so as to then move on to its

main notions and applications in the context of aircraft computerised design environments. The fact that such a relationship exists between design packages and KE, which itself is tightly connected to the field of AI as it will be developed below, further strengthens the interest of integrating this subject within the research conducted during the doctoral studies. Building upon the overview of KE provided in the aforementioned subsection, here a broader perspective of this field shall be expounded, emphasising its connection with AI.

Depending on the viewpoint of each reference, KE can be considered as an area within AI (227), or as a separate, but related discipline (226). Two definitions on the subject of KE, as obtained from references concerned with the general fields of AI and KE, were already given in 4.4.1 as follows: *“the area of artificial intelligence that is concerned with the design, development and maintenance of agents that use knowledge and reasoning to perform problems solving and decision making tasks”* (227), and also *“the process of developing knowledge based systems in any field”* (226). It is seen that these definitions emphasise Knowledge Based Systems (KBS) as a key practical product of the activities of KE. The intelligent agents that have been commented beforehand in this text are precisely considered one of the possible types of KBS (226). The process itself of building KBS has been described as: *“building a computer model with the aim of realizing problem-solving capabilities comparable to a domain expert”* (234). In this same reference, the viewpoint of building KBSs as a modelling activity is highlighted, emphasising the ways in which these models provide an approximation of a certain reality which is sought to be represented (234). The approach of representing in computer systems certain abstractions of reality has also been related to the OO paradigm in previous works such as those of (12; 229), with this viewpoint as well as its relationship with KE having been expounded previously in this thesis within 4.4.1. Further perspectives on the relationship between the domains of AI, KE, and other subject areas can be found in references (226; 227; 233; 271).

In order to implement knowledge within a KBS, it is firstly required that this knowledge is acquired. This process, called knowledge elicitation or knowledge acquisition, is a complex endeavour which precedes knowledge representation and implementation (226). In fact, it has been recognised that knowledge acquisition is one of the main bottlenecks towards the development of KBS (272), which usually lengthens the development of KBS considerably, particularly when building knowledge from scratch (273). More details on this process, its main difficulties and methodologies to conduct it can be found in (226).

Knowledge in intelligent agents is modelled within a Knowledge Base (KB), which can be defined as *“a representation of facts, expressed in a certain knowledge representation language”* (233). This knowledge base usually contains interpreted information on the way that the environment works and on how different actions impact it. As mentioned above, knowledge can be of many kinds, and this has a direct relationship on the possible

ways in which it can be represented and codified. Knowledge representation paradigms can be of different kinds, such as semantic networks or frames (226). Some authors even consider implicit knowledge representation schemes, such as patterns extracted from data (76; 226; 274). At the same time, these representation paradigms employ different knowledge modelling components as building blocks to construct the representation. Depending on the paradigm, these can be concepts, roles, rules, cases, etc. (76). As anticipated beforehand, the knowledge base is essential so that an agent can be considered intelligent. An agent that just performs actions at random and selects those that yield the best result, might not be considered truly intelligent (233), as its actions are driven by automatic cause-effect and not through an internal interpretation and reasoning of the effects that these actions provoke in the environment. This is an additional point which strengthens the notion that codifying knowledge in computer-readable formats towards its use by intelligent agents is one of the key aspects of AI.

Learning is also one of the key aspects of intelligent agents. It can be considered as the way in which the agent generates new knowledge, both from existing one which is already in its KB, and also from its experience when operating with data from the environment. In the same way that there are different kinds of knowledge, there are varying approaches towards learning. For instance, an agent can generate new knowledge through a process of logical inference conducted on the existing KB (227), for which this knowledge must be codified in a particular way so that it is compatible with logical reasoning. Another possible way of learning is through data, where patterns and trends are extracted following a data-driven approach (226; 274). A more detailed exposition of different learning mechanisms can be found in (233).

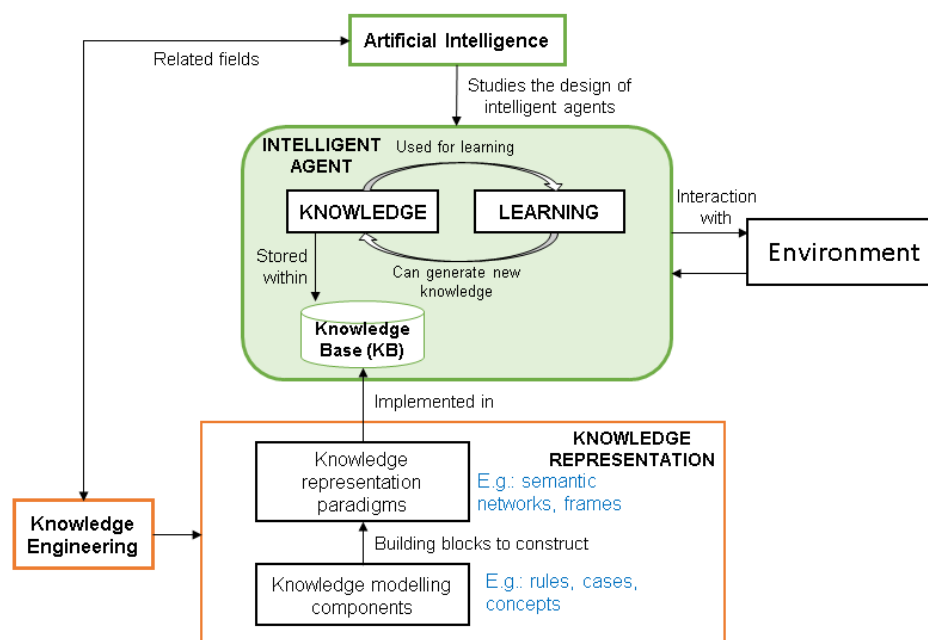


Figure 5-1. Conceptual map of the intelligent agent, its main dimensions, and their relationship with knowledge representation elements.

The concepts introduced until now, as well as their relationships, are illustrated in Figure 5-1. Of particular interest is the distinction between the knowledge represented within the KB, which is a component of the intelligent agent, and the intelligent agent itself.

The fundamental role that both knowledge and learning play in the design of intelligent agents, along with the different ways of representing and codifying knowledge, as well as the distinct learning methods, can serve as key dimensions to distinguish various approaches within the domain of AI. In fact, in the following pages, two different AI approaches, with each placing emphasis in distinct ways in which knowledge can be represented and codified within the agent, the usual learning mechanisms to expand this knowledge, and the way in which the knowledge is employed by the agent.

(c) AI approaches: symbolic and subsymbolic AI

Towards the research, analyses and discussions to be expounded within this chapter, it is crucial to use as a basis a classification of AI approaches. There is a vast number of AI techniques, each of which emphasises different methods of knowledge and learning, as well as ways of using their knowledge. Therefore, each of these techniques shall have differing characteristics and types of problems for which they are more suitable. When analysing potential uses of AI in aircraft design, the different qualities and weaknesses of these groups of AI techniques shall aid to pinpoint their ideal areas of application in RPA design.

As with the definitions of AI, there is an ample number of possible taxonomies as proposed by different authors, with varying categorisation criteria. For example, some of them emphasise the goal of the intelligent agent (233), others focus on different types of intelligent behaviour (226), and others are centred on whether the process that leads to a given output can be explained or not (275), among other possible criteria used to group AI techniques. The classification considered in this thesis follows a classical approach, based on that employed by Lieberman (276). Here, AI techniques are categorised according to the following considerations, which have also been considered as paramount distinguishing features in other works (274; 277):

- The way in which data, information and knowledge are represented.
- The learning paradigm used to obtain new knowledge.
- The way in which knowledge is leveraged in their applications.

This classification schema results in two main groups of AI approaches: symbolic AI and subsymbolic AI. Their definitions, main features, and a sample of AI techniques included in each of these categories, shall be expounded below. A summary of these aspects is provided in Figure 5-2. It should be noted that the classification considered here, including the distinction between symbolic and subsymbolic AI, has been used, with some changes, as a basis for those employed in other recent works. This is the case of research

in the field of AI, such as in (274; 278), and also in taxonomies proposed by Aviation Authorities (65), as seen and discussed in (279). Overall, this proven classification continues to offer a relevant conceptual framework for the study and categorisation of AI techniques.

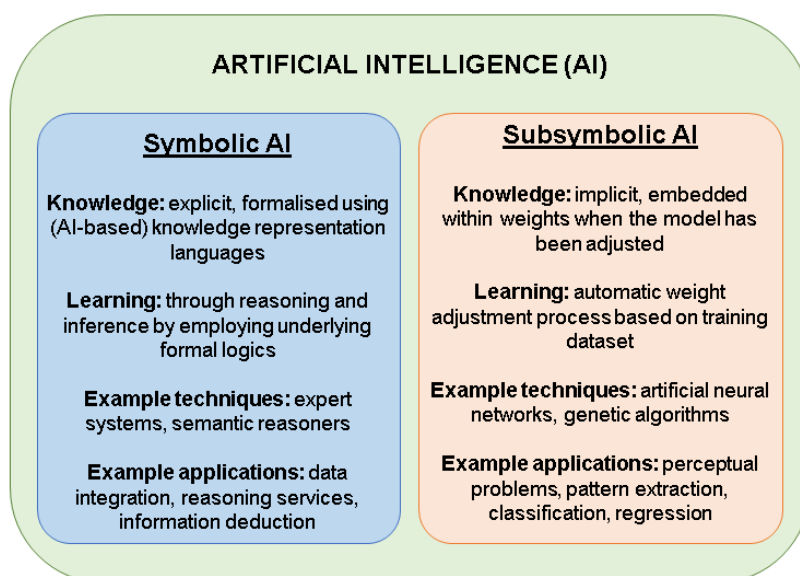


Figure 5-2. High-level comparison between main features of the two main branches of AI considered within this thesis. The characteristics are developed in detail within the text.

In the following exposition of the aforementioned branches of AI, some characteristics which are particularly related to safety, such as explainability or transparency, shall be mentioned. As anticipated before, and as it will be commented more in-depth in the following subsection, the assurance of the safety of AI techniques towards their integration in aviation products and services is fundamental, due to the high safety demands in this domain. Further details on some of these safety-related features, as well as an exposition on the current demands of Aviation Authorities, shall be discussed in more detail within section 5.2.

(c.1) Symbolic AI

The branch of symbolic AI is based on the philosophical notion that “*intelligence, in both humans and machines, is a matter of manipulating symbols according to fixed and formal rules*”, and that “*symbol structures are capable of designating objects in the world and area also capable of designating processes*” (280). Therefore, it is clear that symbolic patterns (which are mainly used in this case to represent declarative knowledge), as well as the rules for interpreting and operating with those symbols, both play a key role in this area of AI.

When thinking and reasoning, humans communicate ideas, concepts and conclusions through natural language, which is the most widely used of knowledge representation

(270; 277). Natural languages are constituted by systems of symbols, sounds and images. The field of semantics studies the relationship among the thought or reference (which is the mental concept of that which is communicated), the referent (which is the corresponding element in the world), and the symbol (which is the linguistical representation of the mental concept) (277). Computers, on the other hand, also employ a language, which at their most fundamental level, is the binary numeral system. Drawing a parallel with natural languages, symbolic AI seeks to develop artificial languages, also called computational languages, which allow to represent within a computer system the accurate meaning of concepts as well as the relationships between them. These paradigms should not only enable the computer to understand the meaning of terms, but also to conduct reasoning tasks employing those concepts, in a similar way to that performed in human rational thought and communication processes using natural language. This combined approach would enable computers both to understand the essence and meaning of concepts, as well as to reason with them (277).

There are many other fundamentals of symbolic AI which are related to the comparison between natural and artificial languages, and of knowledge representation paradigms and reasoning processes in both humans and machines, which would fall outside the scope of the theoretical background presented here. These topics are developed in full detail in references (270; 277; 280).

Considering the approach mentioned above of employing artificial languages to allow knowledge representation and reasoning in machines, it is relevant to draw a parallel with the aforementioned notion of intelligent agents by Russel and Norvig. It was commented that intelligent agents employ both knowledge codified in a KB, as well as learning mechanisms, to search for solutions to the problem at hand (233). In the case of symbolic AI approaches, knowledge will be codified employing formalisms that are based on symbolic representations, and more specifically, on the previously mentioned artificial languages. These languages are implemented in such a way that they are computer-readable, which is essential so that the digital computer agent can leverage the knowledge represented employing them. This knowledge representation approach is accompanied by a series of algorithms which constitute the basis of the reasoning or inference engine, that is the part of the agent which allows the reasoning of new knowledge from that which has been originally declared. In this way, from a set of initial symbols, which represent the pre-defined declarative knowledge, the computer can generate new symbols, which characterise the conclusions; all codified according to the artificial language. In the specific area of symbolic AI, these two elements (the artificial language with its explicit symbols and meaning, and the inference engine), link with the general concepts of knowledge and learning as fundamental dimensions of an intelligent agent according to Russel and Norvig's definition, thus connecting the general AI paradigm with the specific one used by symbolic AI approaches.

One of the most usual ways to codify knowledge in the field of symbolic AI is through the use of knowledge representation languages (233), which constitute a particular approach within the realm of artificial languages. These knowledge representation languages are defined by both their syntax (the symbols that constitute the language, as well as their possible configurations) and their semantics (the way in which symbol combinations are interpreted to extract the knowledge represented within). The explicit definition and codification of semantics in a representation language is considered a fundamental step for developing intelligent systems, as it has been regarded that manipulation of symbols only attending to syntax, and without considering their meaning (semantics) does not truly constitute intelligence (280). When both syntax and semantics are precisely defined, the language is called a logic. For instance, first-order logic and description logics constitute relevant knowledge representation languages. These kind of artificial languages allow to derive a formal mechanical procedure which lets the computer extract the knowledge that is represented in the different symbol combinations, as well as to conduct logical inference procedures to reach conclusions regarding this knowledge codification, which can allow amongst other aspects to arrive at new knowledge (233). The capabilities of a knowledge representation language are heavily dependent on the formal logic employed in its modelisation and codification (281). This in turn has a direct impact on the knowledge representation capabilities (for example, whether constraints or axioms can be implemented or not) and on the reasoning services that will be supported by the language. Thereby, the properties of these artificial languages have a decisive impact on the capabilities on the symbolic AI systems that employ knowledge bases codified in these languages.

Furthermore, it should be noted that there are other types of artifacts which can be employed for knowledge representation and codification in a KB, many of which are themselves formalised on knowledge representation languages. Ontologies are a noteworthy case of semantic artifacts which serve to represent knowledge. Their formal definition and capabilities will be commented and discussed in detail later on in section 5.3.2. In a broad sense, they are formalised vocabularies of terms with explicitly defined meanings, which also include a representation of the properties and the relations between such concepts. The way in which they link with the topic of interest here is that they can be one of the forms to represent and formalise knowledge in a KB, so that symbolic AI techniques can then employ it to perform complex tasks. The topic of ontologies will be central for the investigation conducted in this thesis dealing with the use of AI methodologies to enhance aeroplane and RPA computerised environments, which will be developed in section 5.3.

In summary, symbolic AI approaches emphasise the use of artificial languages, and in particular knowledge representation languages, which have explicitly defined syntax and semantics. These are used to represent concepts and their relationships in such a way that a computer can understand the underlying knowledge represented by the language, and perform it for reasoning tasks, which among other aspects allow to deduce new

knowledge. The agent can then use the conclusions it extracts from its knowledge and learning processes to interact with its environment. It is of particular relevance to distinguish between three elements:

- **The knowledge built on the agent's KB**, which is represented using various possible knowledge representation formalisms, such as for example ontologies. This is related to the knowledge dimension of the agent.
- **The inference engine**, which allows the agent to perform reasoning tasks on the knowledge stored within its KB. This capability is enabled by the underlying formal logics with which the knowledge has been codified. This is related to the learning dimension of the agent.
- **The intelligent agent itself**, which is the entity that employs the knowledge stored in its KB as well as the conclusions that it obtains from the learning process in order to interact with the environment.

It can be seen that the symbolic AI paradigm has a particularly tight interdependency with the field of KE, as it places a remarkable emphasis on the formalisation of explicit knowledge, reasoning, and explainability (277), which are concepts that shall be key in the future discussions to be developed in this chapter. There are further links with KE and the concepts introduced beforehand related to this field. For instance, the knowledge built on the agent's KB can be considered to represent a certain modelisation or abstraction of the subject matter, connecting with the perspective of building KBS as a modelling activity as mentioned beforehand (234). The knowledge representation paradigms which are of most interest here are those based on artificial languages, as their formal syntax and semantics allows to conduct the reasoning tasks commented above.

The knowledge and learning components of the intelligent agents based on symbolic AI have been explored above. Moving on to the agent itself, there are different models, techniques and approaches to leverage the aforementioned two main components and thus to build intelligent agents based on symbolic AI. Some relevant symbolic-based AI methods include: inductive logic programming, search-based algorithms, decision trees, cognitive assistants, semantic reasoners, and expert systems. Here, a brief account shall be given of the latter two, which are most related to the developments and research of this chapter. A more detailed account on the variety of symbolic AI approaches and models can be seen in (65; 226; 227; 274; 276; 280).

- **Semantic reasoners:** this symbolic AI approach encodes knowledge by employing ontologies, which are a particular type of knowledge representation paradigm as commented beforehand. Taking advantage of the formal semantics which can be encoded within ontologies owing to the use of AI-based knowledge representation languages, the semantic reasoners, which would be considered a

type of reasoning engine, can infer new axioms from the existing ones, thus leading to the extraction of new knowledge.

- **Expert systems:** they can be defined as “*an intelligent computer program that uses knowledge and inference procedures to solve problems that are difficult enough to require significant human expertise for their solution. The knowledge necessary to perform at such a level, plus the inference procedures used, can be thought of as a model of the expertise of the best practitioners in that field*” (227). They are sometimes divided in those based on Rule-Based Reasoning (RBR), which use reasoning by logic; and those built on a Case-Based Reasoning (CBR) approach, which use reasoning by analogy (244; 274). It should be highlighted that the latter one tend to employ a KB built on cases, which can be considered as set of problem-solution tuples. This serves to showcase the different knowledge representation paradigms that are linked with distinct types of intelligent agents or approaches.

The main applications of symbolic AI techniques include the development of knowledge models to annotate data, heterogeneous information integration, using reasoning to deduce new knowledge from the pre-defined base, and conducting reasoning tasks with potentially incomplete or even contradictory knowledge, amongst many others (276; 277). Some of the main advantages of symbolic AI techniques include their clarity in representation and processing, leading to an enhanced transparency and explainability (226; 276). Since the KB is formed by explicit knowledge, which can be represented in ways that are easily understandable both by humans and machines; and the reasoning rules are also codified according to formal logics; it is feasible to trace the steps which lead the symbolic AI model to reach a certain conclusion. In fact, Semantic Web technologies, and particularly ontologies, have been considered ideal candidates to design explainable AI algorithms (282). Furthermore, the foundation of these techniques on formal knowledge and rules lead to a noteworthy processing accuracy (226), which is also related to higher levels of reproducibility and robustness.

On the other hand, these approaches also present certain disadvantages. Since symbolic AI models are heavily knowledge-dependent, it is important to carry out an adequate knowledge acquisition activity. This task, as mentioned beforehand, constitutes a relevant bottleneck towards the development of KBS (272), particularly when building knowledge bases from the ground up. However, the Defense Advanced Research Projects Agency (DARPA) Knowledge Sharing Effort tackled this issue by proposing to construct KBs through the reuse and assembly of smaller and reusable knowledge components (273). In this line, and as discussed in previous works, one of the most promising approaches towards modelling these reusable knowledge resources would be through the use of ontologies (283). These knowledge artifacts also present several other advantageous prospects within the fields of AI and KE, as it will be developed in more detail in section 5.3. On the other hand, another potential drawback for symbolic approaches is the potentially time-consuming effort in writing the rules on which they depend for

reasoning. As a mitigation to this issue, the use of already established and proven logics, such as first-order logic or description logics (281), can alleviate this task and thus the implementation effort. Furthermore, in the case of ontologies, as it will be seen in subsection 5.3.2, ontology languages and tools which facilitate these tasks are already available to the designer.

Overall, in spite of the great advancement and attention in subsymbolic AI approaches, as it will be discussed shortly, symbolic AI models are still have a large influence today (280), and in particular cognitive assistants are thriving in many areas, with some very modern examples being found in (227). The use of symbolic AI approaches in combination with subsymbolic AI, as it will be mentioned later on, constitutes a revolutionary field that is generating a remarkable interest, as seen in (274; 282).

(c.2) Subsymbolic AI

The branch of subsymbolic AI, also known as connectionist AI, seeks to generate or extract patterns or numerical models from large amounts of data. Here, instead of employing symbols, explicit knowledge representations, and logical rules, the subsymbolic AI models handle numerical representations, such as scalar values or arrays (277). Many of the techniques included within this domain derive their inspiration from the modelling of biological processes, seeking to represent capacities such as skill or intuition that cannot be expressed in explicit human language or reasoning (226). Therefore, the kind of knowledge represented in these systems is implicit, and hardly interpretable by humans, as opposed to the explicit and rational one of symbolic AI (226). Regarding learning, they emphasise an automatic approach based on the data which is fed into the model, instead of the formal rules and reasoning-based methods seen beforehand. These dimensions and the way in which intelligent agents based on subsymbolic approaches implement them shall be explored further down the text.

Much of the effort found in the literature of artificial intelligence is focused on a particular type of subsymbolic AI models: Artificial Neural Networks (ANNs). Even in the field of aviation, the main efforts of Aviation Authorities dealing with the subsymbolic domain have been directed towards these models, as seen in (65; 284; 285). Therefore, most of the exposition below is focused on ANNs. However, it should be noted that there are other remarkable subsymbolic approaches, such as genetic algorithms, also called evolutionary algorithms. These are algorithms inspired by natural evolution mechanisms, and they configure evolving solutions based on heuristics to tackle complex problems, (226; 274). They have been used with remarkable effect on optimisation problems, as documented in the domain of aerospace engineering and particularly, in aircraft design, as documented in (61; 64). Other types of connectionist AI approaches aside from ANNs are documented and classified in the works of (226; 274; 280).

ANNs are inspired in the structure and operation of the human brain, and they use this baseline to model intelligent processes (280). Their structure is composed of a large

number of processors, also called units. These are inspired on nerve cells, and have relatively simple input/output functions. These units form a network of connections (also called links) among them, and some are also interlinked with the input and output structures located at the beginning and end of the system. These connections have different weights, which are numerical parameters of the model, not unlike the coefficients of regression models. For each unit, the values of the weights are operated with those of the inputs, and the obtained value defines the level of activation of a unit, which in turn determines its output, which serves as the inputs of other neurons (226; 280). The units can be distributed following many different architectures, which are usually built on layers of neurons. The full system is composed of the net itself, and the aforementioned input and output structures.

The purpose of the neural network is to model a certain phenomenon in such a way that, when a set of input values is provided to the network, it operates them with the different weights along the underlying structure, and gives as a result certain output values which should be an accurate prediction of the event which is being represented. Therefore, the information processing here is a matter of excitation and inhibition of the units, which determine the output (280). As the output is largely dependent on the values of the weights of the multiple links within the network, they have a key influence in obtaining reasonable outputs. However, these weights are, on the outset, unknown.

The process for obtaining an adequate set of weight values follows a similar approach as that employed in a regression analysis, which is itself described later on in this thesis within subsection 7.4.2. The ANN is provided with a set of training data, for which the inputs and corresponding outputs are known. These are used to fit the weights of the models, such that the network's input-output behaviour comes into line with that of the phenomenon being modelled (233). This, in fact, is considered as the learning process of the neural network (76; 233). Once the network has been trained, it can be used to predict the outputs corresponding to inputs for which the results are unknown. Albeit the conceptual approach is similar to that of fitting a regression model and then employing it for predictions, there are many considerations regarding the network structure, the learning algorithm, and cautions to be taken when evaluating and employing the mode. A detailed description of these aspects can be found in references (226; 233).

Returning to the notion of intelligent agent of Russel and Norvig, and in view of the above, it is possible to identify the specific approaches to knowledge representation and learning in the case of subsymbolic AI, and specifically for ANNs. In this case, the dimensions correspond to the following concepts:

- **Knowledge** on the phenomena which the ANN is modelling would be embedded in an implicit manner within the adjusted weights of the network, which represent a system of storage of memory (226). In this way, the adjusted weight values represent generalised knowledge or patterns or tendencies between the inputs and outputs (also called problem and solution spaces) without making the

captured knowledge explicit (244; 274; 277), which is in contrast to the explicit knowledge in the symbolic AI branch. The fact that this knowledge is implicit has a large influence on the transparency and explainability of these models, which are significantly hindered, as it will be commented further along this chapter. Another characteristic which has been noted of this type of knowledge is that the patterns that it represents are usually extracted from features associated with high levels of abstraction (274). Furthermore, it should be noted that this knowledge is also highly pragmatic, being more linked to establishing a correspondence between inputs and outputs, rather than on understanding or representing the basis of the physical phenomena of interest.

- With respect to the dimension of **learning**, it is clear that this corresponds to the process of adjusting the parameters of the model when it is fed with a training set of data. Therefore, the system learns from the training data the functional relation between the input and output spaces, which corresponds to the process of optimising the values of the weights. It should be noted that, as learning for these systems is mostly data-driven, large amounts of data are beneficial for these approaches, and they usually reach their optimum performance when this high volume of information is available (244; 283; 286). This learning process of automatically capturing the knowledge component of the phenomena based on data is called induction (244), and it is related to the widespread concept within the field of AI of Machine Learning (ML). This usually refers to learning algorithms that modify their behaviour based on their learning process based on data and their experience (65; 286). There are further distinctions between learning algorithms, such as those considered in the usual distinction among supervised, unsupervised, and reinforcement learning, the fundamentals of which are developed in references (233; 284).

It can be seen that these mechanisms for knowledge representation and learning are remarkably different from those of symbolic AI, thereby justifying the differentiation between these two AI paradigms.

Two additional concepts that are usually considered within the subsymbolic paradigm are briefly introduced here. Deep Learning (DL) is a notion which does not have a unified definition in the field, however it usually refers to very complex subsymbolic models requiring large computational resources, performing reasoning at larger levels of abstraction, and demanding large dataset volumes (274). One of the most paramount example are Deep Neural Networks (DNNs), which are usually considered as those which have more than two intermediate hidden layers (65; 274). Albeit DNNs tend to showcase higher performance, particularly in scenarios where larger training data volumes are available, they also present steeper explainability and transparency challenges due to the complexity of the models (284).

The second notion to be commented here is the concept of Generative AI (GenAI), also called Deep Generative Models (DGMs) (287), which is currently one of the most up-to-date topics in this domain. This concept usually refers to complex algorithms which typically employ DNNs to produce new contents – text, images, sounds – from a learning process conducted on extremely high-dimensionality datasets (277; 287; 288). These models learn complex patterns from the training data, so that they can then generate equivalent new data (288; 289), exploiting their ability in tackling large-scale problems such as image or text synthesis (290). Some general examples include Large Language Models (LLMs) such as GPT-4, or text-to-image systems such as Midjourney, Dall-E and Stable Diffusion (290). However, their use in problems with safety considerations such as engineering design is still an unsettled area which is currently being investigated (287; 289), as these models present additional challenges when compared to other approaches also within the realm of subsymbolic AI, as it will be commented further below.

Some of the main advantages and applications of subsymbolic AI approaches, with a particular focus on ANNs, are expounded here. These approaches can tackle problems which were considered intractable in a symbolic form (291), some of which are among their main applications, as it will be seen below. In fact, some of their main areas of use are geared towards scenarios where explicit knowledge of the domain is unavailable, which includes when relationships among input-output mappings are extraordinarily complex or not clearly known (233; 244), where they can even detect intricate and previously unknown relationships present in data (226). Their main way to tackle such complex endeavours are through the large quantity of input data used to train them, which allow to adjust their general predictive model to the phenomena at hand (292). Due to being data-driven, their performance increases when a large volume of data is available (244), which is also one of the key factors when identifying their most promising areas of application. Some of their main advantages include their generality, flexibility, tolerance to missing or noisy data, and their support of parallel computing (226; 244).

Owing to their low sensitivity to noise, their generic structures, and their automated way of learning, ANNs can easily be employed in many domains following the same basic principles. In fact, they have been noted to have a wide array of applications (233), being especially adept in those intelligent tasks dealing with perceptual problems, pattern recognition, categorisation, regression, and the prediction of future trends (226; 276; 280). Some of their main applications include: Natural Language Processing (NLP), object recognition, extraction of complex correlations in large datasets, predictive maintenance, content recommendations, optimisation, conversation assistants, and computer vision, amongst many others (233; 277; 291).

However, these models also present some shortcomings. Albeit ANNs allow to solve very complex problems which are difficult to model, showcasing remarkable performance (282), their approach results in a low transparency and explainability of the way in which the model works, including a noteworthy difficulty in understanding their functioning and

in interpreting their implicit knowledge (226; 233; 282; 293). Therefore, in spite of ANNs being able to represent knowledge components to a certain extent, they have been categorised as black-box approaches (244; 293). This is precisely due to their opacity, as the learning process involves the adjustment of the internal weights of the model, and the knowledge is only implicitly represented in the values that they take (244). It should also be noted, as mentioned beforehand, that the knowledge embedded in the net is fundamentally pragmatic, as it is based on matching inputs to outputs, instead of being based on an understanding of the physical basis of the phenomena of study. Therefore, even if the implicit knowledge can be recovered, its interpretation towards achieving explainability is an arduous endeavour (285; 294). Furthermore, as a result of the increase in the complexity of the network models along with that of the learning algorithms that has occurred in recent times, such as in the case of DL paradigms and DNNs, the opacity of the networks has been further aggravated (277; 284; 286). As a consequence from these aspects, there is a remarkable difficulty in comprehending their decision process and the influence of each feature on the output (226; 244; 282; 293). These issues related to the lack of transparency and explainability are critical when considering the use of subsymbolic AI in domains with high safety requirements, as is the case of aviation, as it will be commented in the following subsection of this thesis.

Another relevant disadvantage is that, when seeking an adequate performance level of the model, training sets need to be extremely large (244). Thereby, they are not particularly suited for problems or scenarios where the volume of data available is low. Indeed, it has been recognised that some of the performance issues of complex subsymbolic models, particularly DNNs and GenAI, come from the lack of training data, as these require a massive volume in their training sets to work effectively (277; 295). This brings forth another issue, which is the process of compiling or generating such large volumes of data for training. The above-mentioned aspect has been identified as a remarkable bottleneck in the development and deployment of these models (295).

In relation to statistical aspects, an added issue is that, since the network learns regular patterns, those features that appear less frequently in the training data could be lost in the adjustment of the model (277), in spite of their potential criticality. On the other hand, and regarding very common data elements, a paramount problem of these models can appear, which is known as hallucination. These are particularly significant in GenAI models. They consist on the appearance of incomplete, erroneous, or inconsistent solutions, usually due to the model employing and combining very recurrent elements at times when such use is inaccurate or erroneous (277). These issues are caused by the fundamental way of working of these models, which as commented beforehand, is based on patterns extracted from data represented in the form of scalars, arrays and matrices, even if these correspond to texts, images or other kinds of inputs (277). Since no semantic meaning of the patterns is explicitly represented in these approaches, the aforementioned anomalies regarding data patterns and use can occur. Following with the statistical nature of these approaches, another disadvantage is that the ANN is not able to solve problems

which differ from the problem-solution combinations that it has been fed, limiting its capability to tackle input cases that are relatively far apart from the training ones. Furthermore, a certain level of homogeneousness and continuity of the problem is required. These two latter aspects have been noted as limiting their use in certain synthesis problems (244).

An additional area of concern is that, in spite of the previously recognised wide applicability of these models, they cannot automatically and effectively solve problems without any input from the network designer (233). In fact, in many cases, the decision of certain aspects of the net's structure comes from a process which has a trial an error component that is not negligible. Moreover, up until now, subsymbolic AI approaches have not been as successful in modelling higher cognitive tasks, such as abstract reasoning, formal tasks, and problem solving, which are precisely those which symbolic AI models with higher effectivity (280).

(c.3) Comparison between both AI approaches

Along the previous paragraphs, the characteristics of symbolic and subsymbolic AI approaches have been expounded in detail, along with their advantages and disadvantages. As commented along the text, these features are dependent on the way on which they tackle knowledge representation, learning, and knowledge use, which are remarkably different between both kinds of approaches (277). Here, a brief summary is provided in the form of Table 5-1, establishing direct comparisons between specific aspects. These contrasting points shall be of remarkable for the remainder of the chapter, particularly when discussing which types of AI approaches can be better prepared for certifiability, or which of them can be of greater use for application in different design problems.

Table 5-1. Summary of contrasting aspects between symbolic and subsymbolic AI approaches.

Symbolic AI	Subsymbolic AI
Based on explicit knowledge representation, as well as on rational thought processes	Based on extraction of implicit patterns and trends from data and automatic learning
Employs symbols and artificial languages as essential units	Employs numerical representations, such as scalar values and arrays, as essential units
Adept in modelling abstract problems and thought processes, but can also represent more tangible concepts	Adept in modelling perceptual problems which are complex and difficult to conceptualise. Usually operates at higher abstraction levels
Learning processes follow a deductive and transparent process	Learning follows a statistical and automatic process
Knowledge and learning based on deep and explicit knowledge of the domain and the underlying phenomena	Knowledge and learning are mainly statistical and based on adjustment of weight values
Specific knowledge of the domain or task must be acquired and represented	Similar network structures can be trained for different problems, enhancing flexibility

Symbolic AI	Subsymbolic AI
More useful to explain humans' thought	More useful to extract patterns within data
Low volume of data required	Very high volume of data required
Advantages in transparency and explainability enhance safety evaluation for use in safety-critical domains	Opacity and lack of explainability result in issues when performing safety evaluation for use in safety-critical domains

In spite of their differences, it should be mentioned that both branches of AI consider that information processing can be implemented following a computational approach, be it based on algorithms, logical rules, or statistical processes.

(c.4) Hybrid AI

In view of the complementary characteristics which are shown in many dimensions by the aforementioned two branches of AI, previous authors have identified the potential of combining both approaches, so as to leverage the advantages of both and to mitigate the shortcomings of each of them (226). This is an area of research which is very recently starting to experience a noteworthy development, and is often called hybrid AI (65; 226) or neurosymbolic AI (274; 282). It has been defined as *"a set of approaches for the integration of artificial intelligence models (symbolic and subsymbolic), such that the benefits of both models are combined under a unified approach"* (274). The emergence of this domain has led to a reconsideration of previous classification schemes of AI techniques to include this middle ground, as tackled in the works of (278) and (274). It should also be noted that in the later revision of the EASA AI Roadmap, which will be commented later on this chapter, hybrid AI already appears as another concept within their working taxonomy (65).

Two relevant aspects of this domain are commented here. Firstly, the hybrid perspective allows to improve the explainability disadvantages that subsymbolic systems had, while at the same time leveraging their potential in modelling complex phenomena (282). Secondly, the way in which different kinds of knowledge can enrich the system has been highlighted. For instance, the implicit knowledge which is acquired by an ANN can be extracted, decoded, and introduced to the symbolic system to make it explicit. Furthermore, this can allow to add new patterns of restrictions which were not considered when building the explicit knowledge base (274).

Some recent works in this area recognise that there is still much room for research and development here (274; 282). For instance, up until now, there are very few systematic design methodologies for neurosymbolic approaches, which is an issue that is tackled through the contributions proposed in reference (274). Albeit this area is still in its nascent stages, and would be outside the scope of this thesis, it has been included here as a brief contrast to the comment to the apparent dichotomy in the branches of AI.

5.1.2. Potential uses of AI in aviation and relevance of safety assurance

The domain of aviation has a remarkably high safety record amongst the distinct industrial sectors, which has even followed a general improving trend through history. This level of safety is achieved as a result of many factors, including but not limited to the high qualification of personnel, the ingrained safety culture, accident and incident investigation, thorough processes of testing and analysis, the evolution of best practices and procedures, and the extraordinary emphasis on standardisation, regulatory compliance and safety management (296; 297).

With the objective of maintaining, or even improving, this level of safety, it is crucial to conduct a thorough safety evaluation of any new system or technology which is to be integrated into the aviation landscape, and to adapt the regulations and certification standards as required. This has already been seen in the context of this thesis within chapter 3, with the outstanding and ceaseless effort from Aviation Authorities to regulate the field of RPAS so as to ensure their orderly and safe integration within the aviation system. The particularities of these aircraft did not only require the development of new regulations, but even the main high-level principles of the rulemaking process were revisited so as to adjust them to this new paradigm, such as for instance prioritising a performance-based approach, as commented in detail in section 3.2. Many other such examples exist, such as the development of new AMC and AC for composite materials when they were becoming more widespread in large airliners.

In recent times, the interest in integrating AI techniques and innovations within aviation has augmented extraordinarily. Albeit the field of AI is not new (233), the increasing interest and development that AI has experienced in the recent times has been argued to be caused by three main factors: the capacity to gather and store extensive amounts of data, the increase in computing power, and the development of new AI algorithms, concepts and infrastructure (65).

The study of (64) has documented a wide array of investigations which have studied applications of AI within different areas related to aerospace engineering, showcasing the remarkable interest that exists in the overlap between both areas. It should be highlighted that aircraft design and optimisation, along with drone-based applications, are among the main areas of use of AI identified in this work. The possibilities of AI within the particular fields of ATM (296; 298) and maintenance (299) have also been highlighted. As it can be seen, the opportunities that AI offers in aviation are far-reaching, and the main Aviation Authorities have recognised this fact. For instance, EASA highlights its potential impact in different areas on aviation, such as the use of data-driven AI techniques to manage the immense volume of data within the manufacturing domain, or for improvement of trajectory prediction and optimisation of flight routes in the field of ATM (65; 296). In fact, AI has been identified as one of the main enablers to tackle current challenges in aviation, such as increased system complexity, enterprise competitiveness, and environmental challenges (65; 300). Remarkably, it is considered that AI applications can even serve to

boost aviation safety (297), for instance through its use to extract and detect hidden trends and detect incident precursors from the massive amount of safety data available nowadays, or as a tool to classify and analyse safety occurrences (65).

However, in order to leverage the potential of AI techniques in aviation, it is essential to do this while prioritising the high safety standards of this domain. As with any new technology or system, AI poses particular risks if it is not adequately qualified and employed (297). For instance, as reported in (297; 300), certain data-driven AI algorithms can give uncertain or even unpredictable results when evaluating scenarios that are different from those represented within training data. This links with some of the issues of subsymbolic data-driven AI, as seen in the previous subsection. Some AI models have a distinct lack of transparency and explainability, which may also hinder the confidence and predictability of their results (300). Continuing with aspects related with unpredictability, the complexity of many models, particularly ANNs with architectures presenting many hidden layers adds an additional level of difficulty when trying to envision the results and their behaviour to different inputs (65). Adaptive models which may change their behaviour in run-time constitute an additional difficulty towards predictability, which is extremely difficult to manage in these cases (65; 297). Many of these aspects are related to subsymbolic approaches, but there are some that affect both symbolic and subsymbolic AI approaches. For instance, if the KB or data do not have a sufficient level of quality, the correct functioning of the model can be compromised. In relation with this, if the description of the intended behaviour of the system, or the documentation of the KB or data are not carefully observed, traceability would be negatively affected (65). It should be highlighted that many of the aspects commented beforehand have also been studied within the broad field of AI itself. Finally, ethical and security concerns have also been noted (64; 65; 280).

These are just some examples of the challenges and risks that AI can pose if not adequately designed, evaluated, and employed. Some of these are particularly novel when compared to other kinds of models and technologies whose safety characteristics have already been thoroughly assessed. It should be noted that many of these aspects have also been identified and studied in the broad field of AI itself (301; 302; 303), as they constitute relevant risks in any safety-critical field, and not only in aviation. With all of this, it is clear that prior to the implementation and deployment of aviation AI applications for aviation, they must demonstrate their safety and be certified according to clear and streamlined regulations and standards, so as to ensure that the safety demands of this domain are achieved (297).

However, due to the recent surge in this field, the regulatory paradigm of AI in aviation is still in its nascent stages. Industry stakeholders have shown concern for the current uncertainty regarding regulatory requirements for AI technology implemented in aviation systems, which constitutes a barrier towards leveraging the potential of these applications (297). Recognising the interest of industry in AI, and seeking to establish a

framework for the use of this technology in aviation while maintaining its safety levels, the main authorities have begun an intense work in the development of guidance and regulatory material.

The task of establishing adequate procedures for the safety assessment, evaluation and certification of AI applications also comes with its own set of challenges. In the field of research, and not only in relation to the aviation domain, there is a remarkable attention in identifying the characteristics which aid in ensuring the safety of AI systems (such as transparency, explainability or robustness), and also in the development of methods that can be employed to implement these characteristics in AI techniques, as well as to conduct safety assurance evaluations of these systems (299; 302; 303; 304; 305; 306; 307). A more thorough analysis of these topics is conducted later on in this chapter.

The aforementioned perspectives and techniques towards improving and ensuring the safety characteristics of AI systems from a general viewpoint would need to be evaluated and adapted towards their integration within aviation standards seeking to ensure AI safety. As with any safety assessment process in aviation, the risk level is determined by the consideration of the severity of failure, the probability of failure, and the level of exposition to the risk. The regulatory requirements for systems that can have a severe effect on safety are more stringent than those for the ones that have a reduced effect on the safety margin. Now, considering the application of this principle to the integration of AI systems and techniques in aviation, it must be highlighted that there are a wide variety of AI techniques, as outlined in the previous subsection, each with its own particularities and characteristics; and there are also many different possible areas of application of these AI models. These aspects constitute a complex scenario for the establishment of safety assurance procedures and new certification regulations, which are expected to depend on many dimensions and considerations. Attending to the safety management principles, it is expected that deployment of AI will be faster and more straightforward in non-safety-critical applications than in safety-critical ones (296). It should be noted that the parallel increase in safety and certification demands along with risk is not only a typical approach in aviation (159; 175), but is also in line with the EU AI Act, which lays out additional requirements for higher risk AI systems in all fields, including aviation (268; 298).

Both the development and application of safety evaluation guidance is particularly hindered by the lack of transparency and explainability of certain AI models. Opacity and unpredictability complicate the risk evaluation process, and certifiability as a result, as it may be not entirely clear how the model is arriving at certain results (300). With respect to this matter, it should be highlighted that, to certify a system, the designer must substantiate that it complies with a series of points as agreed with the Authority in the certification basis. These demonstrations must be grounded on formal evidence. However, for opaque, complex, and unpredictable models, or for those lacking in explainability capabilities, this requirement compliance substantiation at the certification

stage is notably hindered, as evidence is much more difficult to collect and use as evidence of the intended behaviour in service (296). The need of updating AI algorithms with certain frequency, as well as systems that learn in run-time, constitute additional layers in this substantiation challenge (298; 301). Finally, embedding AI models in systems along with other non-AI safety-related components constitutes an additional challenge during the certification activity, as the right requirements have to be assigned for each component and/or system.

Albeit the development of AI standards is currently underway (279), there are additional challenges towards establishing and consolidating this regulatory framework. Currently, Aviation Authorities are still in the process of deciding not only the foremost rulemaking directions, but also the expected regulatory structure which will result from the integration of AI standards into the existing system (65). Thereby, it can be seen that the challenges are not only related to the development of new standards themselves, but also affect the high-level organisation of the new regulatory framework.

Overall, it can be seen that the regulation and certification of AI techniques in aviation is an area which is vital towards allowing and streamlining the safe development and deployment of AI techniques in the aviation domain, thus allowing to leverage their potential. However, this area of AI safety in aviation is currently in its nascent stages and faces a wide array of challenges, not only in the research of methodologies for guaranteeing the safety of AI techniques, but also in the development of regulations and standards, and even in the organisation of the rulemaking framework that will structure them.

5.1.3. Rationale and objectives of this chapter in the context of the thesis

The purpose of this subsection is to substantiate the main topics related to AI that shall be studied within this chapter, as well as to rationalise their connection with the other lines of work of the thesis. As mentioned beforehand, the application of AI models within the realm of aviation is an expansive subject covering many different areas where these techniques can be employed (64; 65). In the context of this thesis, and following the formulation of OBJ.2.3, the focus shall be on those areas which connect with the main topics developed through this investigation. Therefore, from the main areas of interest in the state-of-the-art of potential uses of AI within the realm of aviation, those which are more tightly related with the scope and the nuclear topics of this thesis shall be identified. Then, the main reasons for studying these areas shall be expounded, and the research directions to be carried out for each of them will be established.

As expounded beforehand within subsection 5.1.2, the particular characteristics of AI models demand the development of novel regulations and standards within the aviation domain so as to ensure their safe integration in this area. Thus, Aviation Authorities are currently in the midst of an intense rulemaking effort to establish this new paradigm, which must consider both the safety assurance demands of aviation as well as the

singularities of the distinct AI models, which as seen beforehand through subsection 5.1.1, are remarkably dependent on the type of approach which is being considered. With this, it can be seen that the area of AI rulemaking to ensure the safe integration of these technologies within aeronautical applications is one of the foremost lines of current interest at the crossroads of the fields of aviation and AI. This area presents a strong connection with the main topics of the thesis, as the subject matter of airworthiness is at the forefront of the research conducted within the doctoral studies, particularly in relation to its influence on RPA design activities.

Therefore, the first area to be studied within this chapter shall be focused on the current landscape of AI regulations and safety research in aviation. Albeit some general considerations have already been provided in subsection 5.1.2 as seen beforehand, a more in-depth analysis shall be conducted on the current status of the aviation AI regulatory framework, the research on novel methods for AI safety evaluation, and the future prospects of Aviation Authorities for rulemaking in this area. When performing this analysis, the particular features of each of the main types of AI models which may influence their safety characteristics shall be taken into account, based on the background previously provided in subsection 5.1.1. Furthermore, considering that this thesis is focused on RPA, and since the topic of RPAS regulations has already been explored in chapter 3, the intersection of these areas will also be investigated. With respect to this matter, the objective shall be to analyse the potential connections between current RPAS regulations related to design and operations with the envisioned areas of AI application as proposed by the Authorities. Albeit the AI framework is still in its nascent stages, it is possible to discover relevant safety implications and couplings between both AI and RPAS standards, thus proposing original insights on the connections among these distinct regulatory areas and building upon the findings of chapter 3. It is highlighted that this line of work sits at the intersection of two remarkably dynamic areas both in the field of RPAS as well as in the broader domain of aviation, these being RPAS and AI regulations. The rationale expounded above substantiates the first of the lines of research of this chapter, which will be developed in section 5.2.

Moving on to a different topic, and as highlighted beforehand within this chapter, the areas of aircraft design and optimisation, along with that of RPAS applications, have both been considered by previous works among the most promising ones of AI use in the broader aviation domain (64; 65). Within the research presented up to this point in this thesis, it was seen in the survey of chapter 2 that AI-based techniques show significant promise for RPA design, but so far only a few previous works have proposed design procedures within this topical area, thus constituting a key avenue for future research. Furthermore, as expounded through chapter 4, one of the seven main trends within current design environments was that of KBE approaches, and it was even seen that this area could potentially act as an enabler for the future development of other key trends such as those of interoperability and extensibility. The field of computerised design environments, as seen through the aforementioned chapters, is one of the most dynamic

ones in the area of aircraft design, and as highlighted in subsection 5.1.1, the strong connection between KE and AI also establishes a significant link between these computer programs with the domain of study in this chapter. With all of this, it can be seen that the use of AI-related approaches to enhance design methods of both manned and unmanned aircraft constitutes another area of remarkable interest of AI use in aviation which also shows noteworthy connections with the topics developed through this thesis, since its main focal point is centred on RPA conceptual design. Therefore, the intersection between these topics will constitute the second main line of work to be studied within this chapter.

However, the multiplicity of options that could result from the combination of different design approaches related to each of the topical areas considered within chapter 2 with the distinct AI models expounded in subsection 5.1.1 establishes a complex and multidimensional framework. Therefore, in order to delimit the scope of the AI-based design methods to be studied here, it is preferred to focus on a particular intersection between design topical areas and approaches related to AI. This will also allow to extract more accurate and applicable conclusions within the scope of the analysis to be conducted.

With respect to the design topical area which shall be the focus of this study, and going back to the topic of computerised environments, it was seen in chapter 4 that aspects related to software engineering and program workflow are key within many of the trends that were detected in the survey conducted there. Additionally, it was seen that future work was required to further extend the uses of KBE within present-day design packages, particularly in the area of RPAS, where they are not as common. Furthermore, in the conclusions to that chapter, it was highlighted that there would be a need of investigating other possible alternatives to provide further advancements related the main trends within the field of design environments, with AI-based approaches constituting a promising alternative in this regard. This perspective is further strengthened in view of the relationship between KE and AI, as mentioned in subsection 5.1.1, thus also establishing a link between AI approaches and design packages. Therefore, the topic of design which shall be the focus of this second line of work within this chapter will be that of aircraft computerised design environments.

On the other hand, the technique related to the field AI to be studied here should be selected to complement this design topical area. As seen in subsection 5.1.1, the distinct types of AI models are based on dissimilar notions in relation to the concepts of knowledge and learning. Thus, they present contrasting characteristics, and are therefore suitable for different kinds of applications. The decision on the AI-related approach selected for this study should not only be made attending to the potential synergies between the needs of design environments with different AI techniques, but also considering regulatory and safety considerations. These are not only key during the aircraft development process due to the connection between design and airworthiness, but also as it was mentioned in 5.1.1. and will be further developed within the first area

of research of this chapter within 5.2, distinct AI models show very different features, and these can have a direct influence in their safety characteristics. Therefore, it is seen that the results from the first line of work of this chapter shall influence this second area, and AI approaches that are aligned to a higher degree with desirable safety features will be preferred.

As it will be substantiated in detail later on in this chapter, and in view of the criteria mentioned beforehand and after analysing the types of AI approaches which have been used until now in different areas of manned aeroplane and RPAS design, the research developed in this second line of work will be focused on the opportunities and challenges of the use of ontologies as knowledge representation paradigm for their use in computerised design environments. As anticipated in 5.1.1, ontologies are not an AI technique themselves. Rather, they constitute one of the options to represent the essential knowledge component that symbolic AI models, such as expert systems, require to operate. Ontologies present many advantages when compared to other knowledge representation paradigms, with one of the main being their embedded semantics, which allow for enhanced reasoning mechanisms. Furthermore, they are also valuable as a data model by themselves, and many of the possible applications that will be proposed for their use in computerised design environments shall be based on this perspective. Their use in design processes is also supported by the safety-related findings of section 5.2, as they present remarkably high transparency, explainability and predictability characteristics, both by themselves as well as within the symbolic AI approaches with which they can be employed.

With all of this, the main purpose of the second line of work of this chapter, which shall be developed in section 5.3, will be to explore the current landscape of ontologies in areas related to aircraft design, and to propose potential areas of applications of these semantic artifacts within the field of manned aircraft and RPA computerised environments. Before delving into these objectives, this section will expound a specific theoretical background related to ontologies, as well as a more thorough substantiation on why they have been selected in this second line of work which is related to the possible ways in which approaches related to AI can enhance aircraft design endeavours. As it can be seen, this line of work also at the crossroads of two notably dynamic fields in the state-of-the-art which are related to the topics of the thesis, in this case being the ones of computerised design environments and AI applications in aircraft design.

With this, the two main areas lines of research that will be developed in this chapter have been outlined. These are related to both aspects provided in the background of the present section, as special emphasis is given both to the different types of AI models and also to including safety and regulatory concerns in the study to be conducted here. Furthermore, it can be seen that these two lines of research are strongly linked with other topics and chapters of the thesis. The first one is tightly connected with the topic of RPA regulations as developed in chapter 3, and also with the relevant gap found in

airworthiness aspects in RPA design as detected in chapter 2. The second line of research is mainly linked with chapter 4 dealing with computerised design environments, and seeks to tackle some of the current gaps and opportunities of future developments in design software packages which were noticed in the aforementioned chapter. A conceptual mapping of the lines of research to be conducted here with other topics of the thesis and also with some of the main areas of application of AI seen within the state-of-the-art is shown in Figure 5-3.

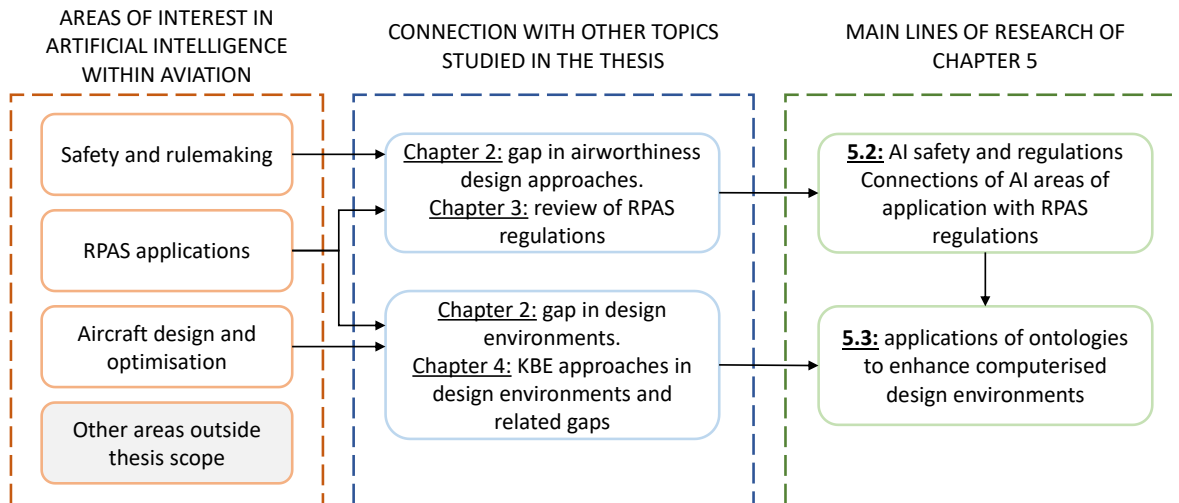


Figure 5-3. Conceptual schema illustrating the relationship of the two main lines of research of chapter 5 with the areas of interest of AI within the aviation domain and with the topics studied in previous thesis chapters.

5.2. AI safety and regulations in aviation and link with RPA

As anticipated in subsection 5.1.2, in the last years Aviation Authorities are carrying out a remarkable effort to lay out the fundamentals of the future AI regulatory framework, so as to enable the evaluation and certification of AI approaches to be integrated within aviation systems, thus ensuring that the safety levels of the aviation domain are maintained. These efforts are, for the time being, in their nascent stages, and specific provisions for the certification of AI systems have yet to be laid out. The overview outlined beforehand shall be further detailed within subsection 5.2.1, which includes details on the current outputs from Aviation Authorities regarding their high-level principles in regulating AI, as well as some initial guidance which is already available.

In parallel, there is a noteworthy advancement in the field of research, both in the broad AI domain (294; 303; 307), and also specifically in its intersection with aviation (306; 308), to analyse potential characteristics that make AI models safer, and also procedures to provide AI models with the aforementioned safety-related features, as well as to evaluate their safety level. It has been noted that these aspects could potentially be related to the future specific AI regulations established by the Authorities attending to their

current proposals (306). Thereby, an overview of some of the aforementioned approaches towards achieving safe AI models are also commented in subsection 5.2.2.

Then, in subsection 5.2.3, the future rulemaking directions and criteria as currently laid out by the main international Aviation Authorities are also expounded, as they constitute fundamental considerations for the analysis of connections between the RPAS and AI regulatory paradigms that will be conducted in the following subsection.

With these findings, and recovering the thread of the RPAS regulation survey of chapter 3, subsection 5.2.4 develops the analysis of connections and influences between RPAS regulations and the main envisioned areas of AI application. This constitutes an original contribution of this thesis, which unveils some couplings between safety considerations in both fields, as well as challenges in the integration of AI considerations within the current RPAS airworthiness framework.

5.2.1. Overview of current outputs from main aviation entities in matter of AI

Here, a brief overview shall be expounded on the main documents, their contents, and the current situation on AI regulation as developed by the main civil international Aviation Authorities. These shall be ICAO, FAA and EASA, which have all begun studying the field of AI and have already published relevant documents in this area. Furthermore, the position and analysis of EUROCONTROL shall also be included, due to the relevance of this institution in the European area of ATM.

(a) ICAO

Considerations of AI aspects in the framework of ICAO have been found in three official documents, which are the following Working Papers (309; 310; 311). They deal with high-level directions relative to the strategy to be followed by the organisation in matter of AI activities, including rulemaking. Specifically, the Working Paper (309) acknowledges the future need to revise existing SARPS to account for AI aspects. It is also highlighted here that the Working Paper (311) emphasises the potential of AI to improve aviation safety, which is one of the main potential advantages in relation to introducing this technology in aviation, as already commented in subsection 5.1.2. As is usual with these kind of ICAO documents, the provisions are very general, and they set the course for future actions from the organisation.

As far as it has been found in the doctoral research, currently no specific AI aspect has been implemented in the main SARPS of ICAO. However, the organisation has organised in the past years a series of conferences and presentations dealing with the future applications, perspectives and challenges of AI in aviation, as seen in (300; 312). Some more specific aspects are tackled in them, such as the issues of unpredictability and lack of explainability of some models. Thereby, it can be seen that ICAO is currently working in this area in parallel to other Aviation Authorities. Considering the wide-reaching impact

of their outputs in the global aviation domain, it is important to remain attentive to their future works in this field.

(b) EASA

Arguably, up until now it could be said that EASA has developed the most intense activity regarding AI policy and rulemaking among the different Aviation Authorities analysed here. The main documents that they have produced, along with the chief directions they envision for AI rulemaking, are developed in the following.

The first formal deliverable by EASA on the topic of AI policy was the EASA AI Roadmap, the first edition of which was published in 2020 (313), and an updated version issued in 2023 (65). This document covers the main perspectives of EASA on AI, including opportunities, challenges, main concepts towards AI safety assurance, and also the envisioned rulemaking concept and timeframe. One of the most important concepts introduced here is that of AI trustworthiness, which is the basis for the future EASA paradigm to evaluate AI readiness for use in aviation. It is based on four building blocks which encompass a trustworthiness analysis, the assurance of the AI system, the consideration of AI-related human factors, and the risk mitigation of the AI technique. This schema is illustrated in Figure 5-4. The second version of the roadmap offers a more detailed overview on the main objectives of each of these blocks, and a life cycle model for the application and AI is included. Showcases the four blocks along with the internal topics for each of them. One of the most relevant aspects to be noted, is that the trustworthiness analysis does not only include safety aspects, but also ethical ones connecting with the EU Ethical Guidelines for AI, and also security considerations. The full details can be consulted in the AI Roadmap (65), and the works of (279) and (306) also offer relevant insights regarding each of these building blocks.

A noteworthy aspect of the update on the Roadmap is that, while the first edition focused only on ML approaches, that is, on subsymbolic AI, the second issue already considers other types of AI, including symbolic and hybrid models. EASA emphasises that the inclusion of these AI types has been one of the main reasons driving the update on the Roadmap, and that one of the main reasons for including them now is the perspectives that they offer on meeting the high safety standards of aviation. This highlights the opportunities that symbolic AI can offer in terms of safety, as already anticipated in section 5.1. Finally, it should be noted that the rulemaking organisation that EASA proposes, which is the way in which the regulations and guidance material that they will develop for AI, as well as their connections with existing regulations, shall be commented in more detail later on this subsection.

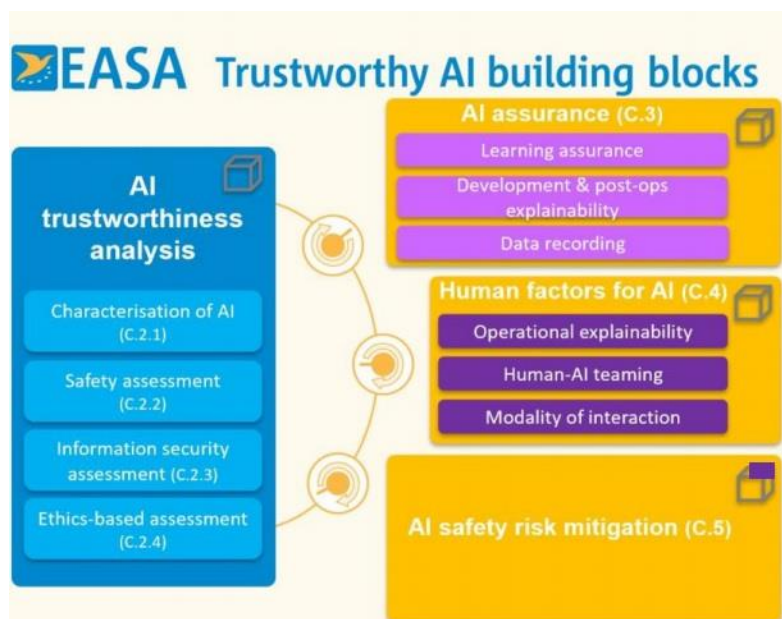


Figure 5-4. EASA schema of trustworthiness evaluation of AI system, based on four interconnected building blocks. Retrieved from EASA AI Roadmap v2 (65) and Concept Paper v2 (284).

Another relevant deliverable by EASA is the Concept Paper on Artificial Intelligence (AI) and Machine Learning (ML), the first edition of which was published in 2021, with the second being edited in 2024 (284). This document delves into a higher level of detail than the Roadmap, and it provides more specific guidelines relative to the trustworthiness building blocks introduced in the Roadmap. It should be noted that the main focus of this document is on ML models, with a particular emphasis on ANNs. Therefore, the safety assurance approaches are particularly tailored for these AI models. For instance, in the development of the AI assurance block, they propose a W-shaped learning assurance model for ML algorithms. This is based on the V-shaped schema of systems engineering, as commented in subsection 2.1.2, but adding an additional intermediate stage for learning process verification. Furthermore, the document provides two annexes including an evaluation on the possible impact on Means Of Compliance in relation to the main aviation domains, and also proposing several use cases (284). All in all, this document provides a higher level of specificity and constitutes a significant advancement towards the formalisation of certification processes for AI in aviation. It is expected that a finalised guidance for these type of applications shall be ready in 2026 (65).

Other significant deliverables by EASA include the Concepts of Design Assurance for Neural Networks (CoDANN), with a first version in 2020 and a second version in 2021, where an appendix was integrated in 2024 (285). These delve in even more specific details regarding ML algorithms safety assurance, such as saliency and explainability, and in fact their findings have been employed in the development of the aforementioned concept papers. Finally, the report from the Machine Learning Application Approval (MLEAP) constitutes another relevant research endeavour by EASA, which also examines the safety aspects of ML algorithms at a high specificity level.

Albeit there is still work to be done, such as the development of specific guidance on other AI models, such as symbolic and hybrid ones, it can be seen that the EASA AI framework has increased at an accelerated pace in these years, and nowadays it constitutes a fruitful resource for future AI research on safety and certifiability also in the academic field.

(c) FAA

Following the publication of the Executive Order 14110 of October 30, 2023, on Safe, Secure, and Trustworthy Development and Use of Artificial Intelligence, the FAA has issued the first edition of its Roadmap for AI Safety Assurance in 2024 (297). This document proposes a high-level overview on the main policy criteria of the FAA on future AI safety evaluation standards and procedures.

The main perspectives of this document can be summarised in the following points:

- It is considered that most of the safety implications of AI systems are already accounted for in the traditional FAA regulations and policies, which are to serve as the baseline for AI regulation in the FAA paradigm. It is recognised that these traditional regulations should be complemented with additional guidelines to cover AI-specific aspects, and it is suggested that these could come from industry consensus standards. Regarding this point, it is highlighted here that this is in line with the FAR/CS-23 regulations reorganisation paradigm, as seen beforehand in chapter 3, and on the other hand it presents certain contrast with the EASA framework, where a higher emphasis is placed on the development of new concepts of assurance.
- Albeit ethical considerations are to be considered within the safety assurance process of AI, for the time being their potential influence is left for future documents.
- The main distinction between AI models is made between “learned” and “learning” ones, instead of a categorisation more in line with that of the global AI domain as seen in 5.1.1. The distinction made by the FAA considers that the verification of an algorithm which has already been trained, and thus its weights are fixed, constitutes a much more feasible endeavour than the same prospect for a model that is learning and thus updating its weights online. Challenges related to the typical high frequency on the update of AI algorithms are also discussed.
- The main guiding principles towards safety assurance of AI are based on Overarching Properties (OPs), whose framework can be divided in three parts: intent, correctness and innocuity.
- The harmonisation of the AI approval framework with other Authorities such as EASA is highlighted as one of the main objectives.

Aside from these aspects, the FAA also includes in the document some AI-related research projects with which they have been involved, providing a source of previous experience for their future development in this field.

(d) EUROCONTROL

As mentioned beforehand, albeit EUROCONTROL is not among the International Aviation Regulators, it is a crucial stakeholder in the field of air navigation and ATM in the context of Europe. Therefore, their Fly AI Report (296), published in 2020, shall be briefly commented here.

This report develops a thorough analysis on already existing AI technologies in the field of ATM and also explores future directions for application. Some of the main challenges that they identify are the establishment of a common data model, the development of human-machine skills and training, and guaranteeing the safe use of AI, amongst others (296). The report supports the opportunities of AI in enhancing aviation safety and also in improving safety research, which were high-level considerations already mentioned in 5.1.2. At the end, it proposes a series of actions to be undertaken for AI integration, with emphasis on the development of validation methods and standards, including the development of AI-specific guidelines. These are also among the topics covered in this section in the present thesis. It should be noted that the ATM applications that are already deployed which are compiled in the document include the ACAS X concept, which is also applied to RPAS through ACAS Xu, and also the enhancement of RPAS autonomous capabilities as seen in a project developed by the European Defence Agency (EDA).

5.2.2. Current research on AI safety characteristics and methodologies

As discussed in subsection 5.1.2, in safety critical applications, it is crucial to guarantee that AI has a series of characteristics that allow it to achieve the goal of protecting human life (64). In the broad field of AI, the topic of safe AI has already sparked a noticeable amount of interest, with different investigations dealing with identifying characteristics of AI models which are advantageous towards ensuring its safety (294; 303; 307). These studies also usually deal with diverse methods that can be applied to check whether the algorithm presents the aforementioned desirable qualities, and also to evaluate its level of safety.

In view of the still emergent status of regulations and standards towards certifying AI, the research conducted in the aforementioned areas is invaluable, both within the broader domain of AI, and also those that deal with specific scenarios of application within aviation. As it was seen before, both EASA and the FAA are using as relevant inputs for their rulemaking procedures the experience gained in research projects. Furthermore, some recent works such as those of (306; 314) seek to establish a link between the current proposals of AI assurance approaches as proposed by the Authorities and methodologies and considerations developed in different research studies. Considering the potential

connections between the AI safety analysis and evaluation methods currently within the state-of-the-art of research and the outputs that have been produced by Aviation Authorities, an overview is conducted here of research on AI safety, both in the broad field of AI, as well as that which is more focused on aviation.

With respect to the terminology and taxonomy employed in this area, previous works have stated that most often the terms do not have an exact definition, and their meaning can vary depending on the work which is using them and the context (286). This can be expected due to the nascent stage of this area of research. The works of (286; 303; 307) conduct detailed reviews on the diverse concepts of this area of safe AI and their interrelations as seen in other works. One of the most extended notions is that of eXplainable AI (xAI), which is often used to define AI systems which *“AI systems that can explain their rationale to a human user, characterize their strengths and weaknesses, and convey an understanding of how they will behave in the future”* (315). An introduction to xAI can be consulted in (316). As it can be seen, this concept seeks to tackle some of the potential challenges of certain AI models, particularly those of the subsymbolic kind, as anticipated in 5.1.2. It should be noted that, in some cases, the concept of “responsible AI” would encompass not only the aspects required towards AI safety, but also any possible ethical considerations (303). The integration of ethical aspects would be particularly aligned with the emphasis that EASA is placing on this aspect, as seen beforehand.

Before going further, it should be commented that most of the work relative to AI explainability has been focused on subsymbolic AI models, and specifically, ANNs. This can be expected due to the automatic learning and predictive capabilities of these approaches, which have been an extended application in many areas of science and engineering. Aside from their interest, and as anticipated in section 5.1, it is clear that they have significant challenges regarding explainability, which supports the trend of a larger volume of xAI work being devoted to them. Due to the stark differences among distinct AI approaches, it is expected that the methods to provide them with heightened safety and to evaluate their risk level shall be noticeably different for an expert system, when compared to an ANN, for example.

Within the broad field of AI, and aside from the aforementioned works laying out the taxonomy and definitions relevant to the field, many other works have conducted research on potential characteristics of AI systems which can serve to evaluate their level of safety or other relevant qualities. The work of (301) conducts an analysis of several general challenges for the field of AI, and amongst them, many which are related to concepts within the previously mentioned taxonomies are cited, such as robustness, reliability and explainability, amongst others. The research presented in (302) presents a wide array of potential xAI approaches. Of special interest are those that are model-agnostic, as they can provide insights on the learning results through explainability approaches that are compatible with various models, thus increasing reusability. On the other hand, the work of (294) supports the use of directly interpretable models, which as

also stated in the previously cited research of (302), present intrinsic advantages regarding explainability as a whole, and thus also safety and reproducibility.

In the field of aviation, works in different areas have shown interest in safe and explainable AI. Depending on the case, some of these investigations have focused on issues towards the practical application of the current regulations, while others have either developed methods for model explainability or applied existing ones. The research presented in (293) is focused on tactical air combat, and it tackles the issue of explainability for a reinforcement-learning algorithm applied to this problem, developing an explanation policy considering both local and global considerations. The work of (317) develops a review of previous research in the area of ATM to detect the main areas of interest in AI applications, and also performs an assessment of various methods for explainability from numerous previous references, proposing how xAI could be applied to different case problems in ATM. Also in relation to the ATM, but in this case focusing on the paradigms related to RPAS of Universal/Unmanned Traffic Management (UTM) and U-space, the investigation presented in (298) analyses the connections of the currently available regulatory material with the expected use cases in RPAS applications and the envisioned issues related to automation of unmanned operations. With respect to the ways in which different AI models relate to safety characteristics, it must be remarked that in the area of “Trustworthy AI”, this research highlights knowledge-based paradigms as key steps in its evolution, thus linking with the higher alignment of symbolic and knowledge-based models with safety and explainability, as already commented in 5.1.1. The investigation developed in (305) should also be highlighted, as it identifies key technological enablers to tackle challenges of AI certification in aviation, and relates various possible failure modes of AI system with potential elements towards their certification. In the research of (299), the challenges towards achieving explainability are particularised in the area of aviation maintenance. Various xAI models are compiled, and a series of parameters towards achieving different levels of explainability are proposed. All in all, different studies have sought to achieve explainability of their models, as this has been recognised as a key step towards trustworthiness and transparency (293).

Considering the need of augmenting the level of specificity of current guidance on AI offered by the main regulators, and also with the intent of proposing potential synergies between the regulatory frameworks and the research developments in the field of AI, some works have also proposed possible connections or uses of safety AI approaches present in academic research with the main topics of blocks of AI analysis as proposed in the regulator’s documents. Such is the case of (279), which studies and compares the current civil and military paradigms for AI in aviation. Not only are the main frameworks examined, but also some existing guidance documents, both classical and related to AI, are related to the current areas of interest within the military airworthiness paradigm. The work of (314) follows a similar approach, focusing this time on the EASA trustworthiness building blocks, and examining possible connections with various EUROCAE, SAE and ANSI standards, amongst others, which can come to complement the

present framework of EASA. Finally, the work of (306) also uses as basis the building block for AI trustworthiness of EASA, but in this case, for each of the components that form these blocks (such as “operational explainability”) a series of research works from the state-of-the-art are proposed as possible methods or means of compliance with the higher-level postulates of EASA. These works showcase the interest in detecting connections and possible proposals of AI safety methodologies to complement the information laid out by the Authorities, which is currently still in development.

As mentioned beforehand, and as seen along the previous lines, subsymbolic AI approaches, and in particular, ANNs, have received the largest focus on safety and explainability research. This is most possibly motivated by the interest in these algorithms, but it is also reasonable that there is not as much urgency for these studies for other approaches, such as those of symbolic AI, since they natively present many desirable characteristics favouring their safety and explainability. Nevertheless, there is still need for work to be done in this area. For instance, the work of (308) focuses on avionics systems and studies various approaches for explainability of symbolic AI approaches.

In view of the above, it is seen that the area of research on safe and explainable AI is a remarkably dynamic field. The synergy between this area of work and that of the development of rulemaking material for AI safety has been proven in view of the works that have studied possible connections between both areas. It can be expected that the regulators will continue to receive feedback from research activities, which might be used in the development of the finalised guidance materials for AI application airworthiness certification. This step of formalising the findings of safe AI research within streamlined regulations is key, since a uniform framework is required to ensure consistency in the objective level of safety established by different stakeholders participating in aviation operations (298).

5.2.3. Envisioned rulemaking concepts and organisation

Having seen the current status of the material from different regulators, as well as the active research being conducted in the domain of xAI, now the focus shall be placed on the envisioned future paradigm of regulations concerning AI applications in aviation. The organisation of the rulemaking material and its connection with previously existing ones constitutes a key part in the strategy for establishing a novel framework, as is the case here with AI. It should be noted that in chapter 3, the rulemaking scenario for RPAS was thoroughly analysed, and among the findings, it was seen that the CS-UAS envisioned by EASA would be a transversal regulation to the classical CS codes such as CS-23 or CS-25, thus complementing the baseline requirements laid out in them with some specific RPAS ones that would be added to the different base regulations.

In the case of AI, as it was seen beforehand in this subsection, the current regulatory framework is still in its first stages, and there is still the need to tackle various objectives before the regulatory organisation comes to fruition. In the case of the FAA for instance,

their priority at this point is to develop the Policy standards towards future rulemaking (297), and there is still not a set plan on how the different future documents shall be connected among them or with the existing ones. However, in the second version of the EASA AI Roadmap (65), an initial concept for rulemaking was proposed. A graphical representation of their proposed regulation organisation is shown in Figure 5-5.

A first point which is relevant to highlight is the connection of the future EASA AI regulations with the EU AI Act (268), a higher-level regulation at the level of the whole EU. It is seen that the first step proposed by EASA in their Roadmap is to create a specific Part-AI, which will be a transversal regulation complementing other specific provisions. It is expected to include requirements for the authorities, for organisations, and also requirements for AI trustworthiness, following the model of building blocks that was commented earlier. This will be complemented with AMC & GM, and with proposed consensus standards as appropriate. On the other hand, the second step consists of adding particular AI provisions to already existing regulations in different domains, so as to complete the general requirements of the new Part-AI.

Albeit this schema can evolve along time, a parallel can be drawn with the similarly transversal approach followed in the area of RPAS regulations from EASA, as seen in subsection 3.5.1, where the requirements from the transversal CS-UAS would supply those in traditional certification codes such as CS-23, which would be selected for application according to the similarity of the RPA with aircraft in each of those categories.

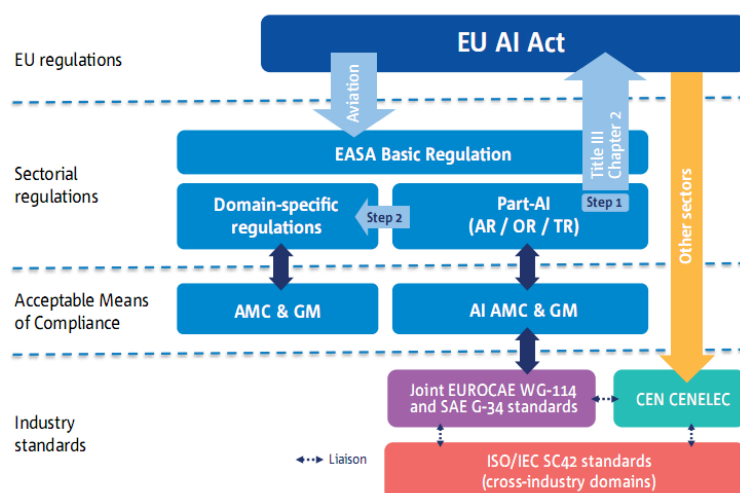


Figure 5-5. EASA concept for AI rulemaking organisation, with a transversal Part-AI and also domain-specific integration of AI aspects in other regulations. Obtained from EASA AI Roadmap v2 (65).

Therefore, there is still a relevant deal of uncertainty on how the regulatory structure of the AI paradigm shall be finally organised, which on the other hand is reasonable considering the nascent stages of this domain. It could also be said at this point that works such as those of (279; 306; 314) which were commented earlier could provide some ideas

on the possible integration of existing AI explainability and safety evaluation methods within the rulemaking framework along its future evolution.

5.2.4. Potential connections between AI areas of application and RPA regulations

As seen before within the current section, both EASA and the FAA have shown extraordinary interest in tackling the rulemaking challenges towards enabling AI safety evaluation and certification in aviation. In spite of this field being still in its nascent stages, the Authorities have established an ambitious timeline, seeking to develop and publish standards in the short-medium term. In the case of EASA, a second issue of the main technical guidance document has been published recently (284), with a finalised version being projected in 2026, other documents for advanced AI applications also on the way, and even an anticipated regulatory structure is already in place to guide the rulemaking process (65). FAA technical guidance documents are also expected to be ready soon, continuing with the efforts launched with their own roadmap (297).

In parallel, as it was seen in detail within Chapter 3, the area of RPAS regulations is also experiencing an intense development, with relevant standards being already in place, and others expected soon so that the framework of the main operational categories is fully covered. Aircraft design and operations, as well as RPAS applications, have been highlighted both by regulators (65) and academic (64) research as two of the main areas where AI could make a higher impact in the aviation domain. Furthermore, there is a concurrent development of regulations taking place in both fields. Considering that the topics of RPA design and regulations are within the core areas of this thesis, and taking into account the potential of AI in these fields as it is being seen in this chapter, a particular line of analysis to be developed in this subsection is proposed.

This line of work consists in evaluating the current and potential future connections and influences of regulatory material both on the side of RPA and of AI. Considering that both areas are still under rulemaking development, this discussion is mostly conceptual in nature, but with the paradigm still being open, it is also a remarkable point in time to assess potential future connections. It should be noted that this discussion is an academic exercise when considering the current state of both regulatory frameworks at this point in time. Clearly the organisation and connections of the regulations is under the remit of the Aviation Authorities, and the applicability of the discussion developed here is fully dependent on their future decisions.

The main scope of the following analysis, which is according to the boundaries of this chapter and of the thesis itself, is focused on the connections between design aspects of RPA and AI considerations. However, as seen beforehand in sections 3.2 and 3.5, one of the main characteristics of the field of RPAS regulations is that design and operational aspects are connected and even appear within the same documents, so operational considerations are also included here. Furthermore, due to the interest of AI applications in the area of ATM aspects related to air navigation and U-space connections with AI are

also considered here. This decision has been made in view of the emphasis on ATM as one of the main avenues of AI application within documents from international aviation stakeholders as studied in subsection 5.2.1 (65; 296), and also attending to its interest in the area of safe AI research as seen in 5.2.2 within references (317; 298), where the high levels of automation expected in the future within this area were highlighted, along with the associated safety and regulatory concerns. Furthermore, due the higher development of regulatory material on the side of EASA on both the field of AI and also in the different kinds of operation of RPAS, the focus shall be on the EU paradigm. However, since FAA has stated in its AI roadmap as released on 2024 that one of its main objectives in the area of AI approval is to seek harmonisation with other Authorities such as EASA, it is expected that some of the aspects discussed here could also be applicable to the future FAA AI framework. In any case, it would be relevant to update this analysis at a later date with the novel developments both on the EASA and the FAA sides.

A conceptual map of the connections among the main RPAS regulations which have been considered in the domains mentioned above, with the main areas of application of AI within the scope of this analysis, as stated in the EASA AI Roadmap (65), is shown in Figure 5-6. In the following discussion, these connections shall be thoroughly commented.

Firstly, the current connections related to AI within the airspace and U-space regulations shall be evaluated. Upon examining the applicable rules for the U-space paradigm, being regulations IRs 2021/664, 2021/665, 2021/666, 2023/203, no explicit mentions to AI-related concepts were found within them. However, one specific aspect to note is that in the GM to Article 7(2) of IR 2021/664, related to connectivity and information exchange in the U-Space between aircraft and U-Space Service Providers (USSP), it is stated that: *“U-space information is exchanged in a machine-readable format to support the necessary exchange of data among the U-space actors concerned”*. It can be anticipated that the potential U-Space paradigm shall require to guarantee connectivity and interoperability among many different elements and stakeholders, such as aircraft both manned and unmanned, and ATM/USSP, with many of these communications possibly being automatic. In Section 5.1.1, it was seen that symbolic AI approaches emphasise knowledge and information representation in machine-readable formats, and they can also perform reasoning on these models to detect possible mishaps, was commented. Considering the above, it is suggested here that symbolic AI models could constitute a relevant area of research towards investigating potential approaches to enhance this interoperability and ensuring through automatic reasoners that the data is set up correctly and according to the data exchange model. However, at the same time, it is recognised that the reasoning operations of symbolic AI are quite computationally intensive, so real-time checks are not expected to be feasible. However, they could be performed beforehand at the flight planning and scheduling stage, so as to ensure that data on flights to be conducted in the U-Space along the following days comply with the standard.

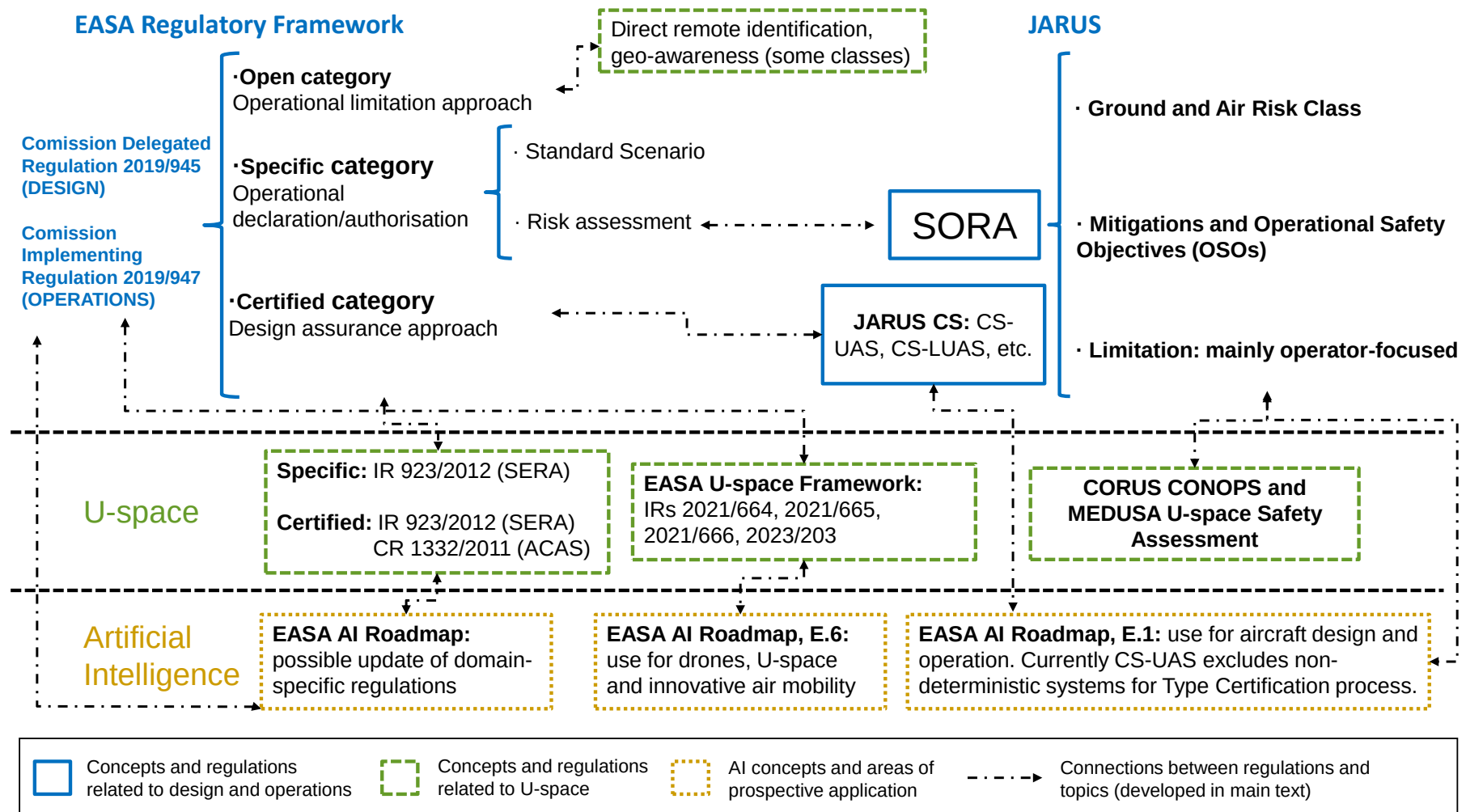


Figure 5-6. Prospective connections among different areas of AI application, as identified in the EASA AI Roadmap, and current standards and rulemaking areas for RPA regarding design, operations, and U-space. SERA (Standardised European Rules of the Air), ACAS (Airborne Collision Avoidance System), MEDUSA (Methodology for the U-space Safety Assessment).

Upon checking the current status of AI-related considerations in the EASA RPAS design and operations regulations, it was seen that neither of the following regulations include mentions to AI, ML or other related concepts: Commission IR 2019/947 (191), Commission DR 2019/945 (192), Commission DR 2024/1108 (208) and IR 2024/1110 (194), which were already discussed in broader terms within subsection 3.5. Thereby, in the broad scenario of RPAS initial airworthiness and operations regulations, these aspects are still not considered. This is reasonable, as the AI framework is still in its first stages, and the priorities of EASA are the development of further guidance documents, then leading to the future Part-AI, before particular AI aspects are integrated in domain-specific regulations (65). Furthermore, some of the aforementioned RPAS regulations were laid out before the kickstart of the EASA AI framework, and the ones which were published later were already for some time in the rulemaking process. Further mentions to AI in applicable AMC and GM documents were not found.

As an additional remark, it is stated in the most recent Opinion No 03-2023 dealing with the development of the regulatory framework for RPAS (318) that among the operational assumptions considered when developing the regulations: *“a human is always in command as autonomous operations are excluded”*. Thereby, in case that AI application certification is included in the RPAS regulatory framework in the future, for the time being it would appear that those that would be related to autonomous control would be outside the scope of the current rulemaking criteria. However, later in the same Opinion (318), it is stated that advanced levels of autonomy are envisioned in the future, which is more aligned with current statements in the AI Roadmap (65).

Regarding the current state of AI considerations in JARUS guidance documents, CS-UAS, which as seen in Chapter 3 is intended for the certified category of operations, states within its applicability considerations that *“Non-deterministic systems are excluded (e.g. artificial intelligence, machine learning)”* (179), which would exclude for the time being possible integration of non-deterministic AI approaches within the design certification of RPAS. AI aspects are not mentioned within the CS-LUAS regulation, which is from an earlier point in time (203). In the case of the SORA v2.5, which as seen in Chapter 3 is geared towards the specific category of operations, only a brief mention is made in the Cyber Safety Extension to autonomous control systems. In particular, this is in the context of required security measures to prevent possible safety threats due to vulnerabilities. On this topic of control systems, it is stated that these systems are often enabled by AI or ML approaches, and that there is still an ongoing effort in establishing guidance on required mitigations for these systems. In view of this, no detailed provisions are given for applicable mitigations in SORA v2.5.

Albeit AI aspects are still not considered within the JARUS framework, this is also the case for other areas of aviation. This is to be expected, as the CS-LUAS date from 2016, CS-UAS from 2018, and SORA v2.5 from 2024; whereas the efforts on AI have begun in recent times. In fact, of the three analysed JARUS guidance materials, it is the most recent, SORA

v2.5, the one which considers future development of guidance material for AI uses, potentially leaving the door open towards integrating specific mitigations for these systems in SORA future versions. It is reasonable that it is the most recent guidance material the one which considers potential future measures for AI validation, whereas the previous ones limit their scope, since the AI framework was by then still not initiated.

In view of the above, it can be expected that the possible integration of AI aspects in the initial airworthiness and operations framework of RPAS shall be gradual, as it is currently the case with RPAS regulations themselves as seen in Chapter 3. Considering the risk escalation considerations from the open to the certified category, and thus in parallel the increasing demand of applicable regulations, it could be likely that a similar rulemaking priority to that followed in RPAS regulations is followed in the integration of AI aspects, with changes to the open and specific category preceding those of the certified category. It is highlighted that, at the current point and as seen in Chapter 3, there are no detailed provisions or certification codes for the certified category of RPAS.

Attending to the current situation of both RPAS and AI regulations, as well as to EASA's stated objectives and criteria on RPAS and AI rulemaking as seen in this thesis, the following text discusses some potential perspectives regarding the possible integration of AI considerations and regulations within the current RPAS framework. Of course, these ideas come from outside the regulator, who is the one conducting the work, and are therefore only a collection of potential perspectives on the current scenario and possible developments.

The safety assurance and certification of AI for critical applications, as commented beforehand, is a much more complex endeavour than the one required for uses with lesser risk. In parallel, the operational categorisation of RPAS is segregated considering the level of risk, and also establishes different requirements for each case. Here, there could be mutual influences of AI and RPAS on the overall risk of the operation, as the category of operation is affected by the operational scenario and the characteristics of the design, which may be influenced by the integration of certain AI system.

As an example, a RPAS operation with baseline characteristics according to the open category is assumed. Now, it is considered that an AI system is integrated which allows for automatic payload camera (not a flying camera) aiming or object identification. It can be expected that any mishap occurring to this system would have a low impact on the overall risk of the operation, as the flying camera is separate, and at the most, this would affect the image acquisition process. As a separate case, it is considered that an AI system for automatic and non-overridable trajectory management is integrated, for instance, to adjust the trajectory in an optimal manner when following an objective. A failure in this system could potentially jeopardise the safety level of the operation, and even the compliance with the operative limitations corresponding the open category. This could happen, for example, if a failure commands the aircraft to exceed the limit height of 120m AGL where open operations can take place, or if it carries the RPA outside the LOS or even

the command link of the operator. Of course, this risk evaluation would have to be conducted considering other algorithms implemented in the RPA which would have higher priority, such as a return home function.

In view of this, it could be that AI applications to be integrated within the RPAS could be limited by the category of operation. For instance, operations in the open category might only allow AI applications with a low level of impact on the risk of the operation. Higher risk AI uses would be left for the certified category, as the designer would have to conduct in any case the effort to conduct the certification of the aircraft system in any case. In the specific category, the type of AI applications could influence the resulting SAIL level of the SORA methodology, as depending on their scope, they could have effect on either the ground risk, the air risk, or both. Furthermore, additional OSOs could be expected for particular AI uses to control the level of risk. It could even be the case that the SORA safety assessment could be required to be coupled with the AI trustworthiness assessment that is envisioned in the EASA AI Roadmap (65), which could further complicate the RPAS risk evaluation.

As it can be seen, there are relevant conceptual couplings between the level of risk associated to RPAS operations and the additional risk that could result from the integration of AI systems, depending on their potential impact. The risk of the AI application could be evaluated not only according to the specific use (for instance, trajectory management), but could also depend on the algorithm employed, as opaque models or ones that are difficult to predict are expected to have a higher inherent risk. This was already anticipated in subsection 5.1.2, where it was discussed that both the risk of the operation and of the particular AI algorithm could be required to be considered concurrently in safety assessment processes.

An added layer of complexity results from the coupling of the rulemaking paradigms of both the RPAS area, as well as the AI area, since they both consider a transversal approach for the consideration of RPAS- or AI-specific aspects, respectively. On the one hand, as seen in detail in subsection 3.5.1, RPAS CS are expected to be organised following a two-dimensional approach, with the bulk of the requirements for RPAS being provided by the applicable “baseline” CS code (CS-23, CS-25, etc.) according to the design characteristics of the RPAS and thus the associated risk level, with the envisioned CS-UAS adding requirements to the baseline CS code so as to consider RPAS-specific aspects, such as those related to the Command and Control Centre, or the telemetry link, among other aspects. On the other hand, the EASA AI rulemaking concept envisions a Part-AI, accompanied by the corresponding AMC & GM, for transversal provisions regarding AI. This is complemented by domain-specific AI aspects which would be added to the particular EASA regulations in each area.

It is not yet known how this transversal approach to AI rulemaking shall be coordinated with that of RPAS. Potentially, it could be that those considerations for specific AI algorithms could be developed in the broader-scope Part-AI, for instance establishing risk

levels associated with the algorithm itself. Then, attending to the RPAS operational category regulations, which could be complemented with AI considerations for this specific area, it is possible that here a relationship between AI uses for RPAS allowed for each operations category, attending to both the algorithm and the application, could be provided. Then, each “baseline” CS could integrate AI-specific aspects which would be applicable to both manned and unmanned aircraft, as those CS, which are the horizontal ones shown in the corresponding figure of subsection 3.5.1, are valid for both types of aircraft. This would result in RPA-specific considerations related to AI being left for the transversal CS-UAS, and also for the CS-Light UAS which is a standalone regulation.

In view of the conceptual complexity of the risk level of the operations and safety assessment couplings mentioned beforehand, and also considering the nascent stages of both regulatory paradigms, it is expected that there is still time ahead for the streamlined integration of AI within RPAS design and operations. On the other hand, it has been mentioned beforehand that RPAS could constitute potential lower-risk testbeds to analyse the safety of AI applications before moving them towards aviation paradigms which demand a higher level of safety. Thereby, it can be expected that a gradual approach towards integration of AI in RPAS could allow to test AI applications of incremental associated risk, which could also go in parallel to their more thorough testing and rulemaking towards integration in other types of operation.

Clearly, the analysis presented here constitutes a discussion on possible challenges and perspectives on the integration of RPAS and AI regulations, considering the current state of the regulatory framework. The development of the novel AI certification framework is still ongoing, so the final relationships between the different materials shall be as established by the Authority, and of course, the applicability of the different aspects from the discussion developed here shall depend on the future directions and decisions by the Authority on the framework and the proposed regulations.

Overall, there is much promise for the integration of AI in RPAS operations, and the nascent stage of both areas in the regulatory area could lead to potential synergies in the rulemaking process. However, the associated couplings and complexities between both of these innovative fields should be examined carefully so as to lay out a robust safety evaluation and certification paradigm which can ensure the safe integrations of both of these concepts within the landscape of aviation.

5.3. Prospective applications of ontologies in aeroplane and RPA computerised design environments

In this section, the second main line of research of this chapter shall be developed. Its topic is that of the possible enhancement of RPA design methodologies through the use of approaches related to the field of AI. More particularly, as outlined in subsection 5.1.3, it is focused on the potential applications and challenges of using ontologies as a knowledge

representation paradigm within the framework of aeroplane computerised design environments. Ontologies are semantic artifacts which allow to represent concepts and their relationships in a given domain. When they are implemented in knowledge representation languages with encoded explicit semantics, ontologies can be leveraged within computer programs for automated consistency checking, interoperability, reasoning, inference of new knowledge, and advanced querying, among other capabilities. Within the field of AI, they are mostly linked to symbolic AI approaches, and can be part of the knowledge base for an intelligent agent of this kind, as seen in Figure 5-1.

The concept of ontologies and their characteristics shall be described in further detail within this section. Albeit some broad ideas on the potential of investigating this particular kind of knowledge representation paradigm within the field of aeroplane design environments were given beforehand in subsection 5.1.3, these shall further be substantiated within this section considering aspects related to both areas, and using as foundation the main trends and challenges of design packages as analysed beforehand in chapter 4.

Before moving forward, and in a similar manner to the criteria which was followed in chapter 4 as commented in 4.3, the analysis to be developed in this section shall not only focus on the conceptual design stage, but it will also consider aspects related to other phases of the aircraft development process. This has been decided due to the fact that this investigation analyses aspects related to design environments, and it was already seen in chapter 4 and quantified in the review of 4.5 that most suites have a comprehensive perspective and cover various stages of the design process. Therefore, albeit special emphasis shall be placed on aspects related to conceptual design, other concepts and applications which are also aligned with further design steps shall also appear here.

The guiding thread of this line of research is as follows. Firstly, to provide some context on the broader area of interest of the use of AI to enhance aircraft design approaches, in subsection 5.3.1 an overview shall be conducted of previous research works tackling the possible applications of AI within aeroplane design. This complements the findings of chapter 2, which were focused on RPA, with some further efforts in the manned aircraft area. Then, subsection 5.3.2 gives a theoretical background on the topic of ontologies as knowledge representation artifacts, including a general perspective on their main areas of use through different domains. With this, and expanding upon the reasons already outlined previously in 5.1 which supported the study on the combination of computerised environments and ontologies within this line of research, this choice will be further substantiated in view of the background provided on ontologies beforehand. These motives also integrate some of the findings related to safety issues as seen in section 5.2 to make this decision.

Then, subsections 5.3.4 and 5.3.5 develop the research proper on ontologies. The first one conducts a review on current ontologies found in areas related to aircraft design, thus fitting within a research effort of type RCT.1. Such a review has not been conducted

beforehand in the open literature, and it offers an updated perspective on the state of this area of research. Furthermore, considering that ontology reuse is a common practice in the field of ontology engineering (201; 207), this survey would also provide the groundwork for identifying existing semantic artifacts towards potential future reuse endeavours. Finally, in view of the current landscape of ontologies in areas related to aircraft design, subsection 5.3.5 conducts the proposal of the main potential areas of application of ontologies in computerised design environments. This would fall within a contribution of type RCT.2, since it proposes novel perspectives on the potential of using ontologies within aircraft design software, so as to leverage the advantages of these semantic representations within a field in which their use is not yet extended.

5.3.1. Outline of current research on aircraft and RPA design using AI

As mentioned beforehand along this chapter, the areas of aircraft design and optimisation, as well as that of RPAS, are among the most promising ones for AI applications within aerospace engineering (64; 65). The practical use of AI-based approaches in RPA design is still in its nascent stages, as seen in the review of chapter 2, where few works in this topical area were found within the state-of-the-art. Nevertheless, as also commented at that point, it is a field which holds remarkable promise towards improving current approaches. This has been seen, for instance, in subsection 4.4.1, where the emphasis on KE within computerised environments was highlighted, and also in the fact that a design package heavily based on AI methods has already been developed, which is the AIDA framework.

In view of the above, this subsection provides an overview on previous works which have delved on the use of different AI techniques for aircraft design. Some of the AI models expounded in subsection 5.1.1 have already been explored in the open literature as part of the potential uses of AI techniques to enhance aeroplane design. The analysis provided here allows to see the different perspectives and AI model preferences up until now, which is one of the main pieces of information that will then be employed in subsection 5.3.3 to make the decision to focus on ontologies in this part of the research. Considering the wide variety of AI techniques available, and also the many different phases and perspectives on the way of conducting the aircraft design process, it is expected that a diversity of applications and approaches shall be found here.

It should be noted that it is not intended to provide in this subsection a thorough review on previous works of AI in aircraft design. Rather, the objective is to focus on some previous investigations to showcase the different potential uses of AI in this area and identify main trends and preferences. A more detailed view is given here on the RPA-related investigations in this area which were already outlined in the review of chapter 2. Furthermore, this will be complemented with other works on the broader field of aeroplane design. It is also highlighted that the topic of the use of KE within the area of computerised environments was already developed within 4.4.1. As seen beforehand, the

fields of AI and KE are tightly connected. Here, the perspective shall mainly be directed towards the realm of AI, and the scope regarding aircraft design is also broader, not being limited to design environments. In any case, this overview can be complemented with the information that was provided beforehand in subsection 4.4.1, where the focus was on the crossroads of design environments and KE.

Regarding **subsymbolic approaches**, it is seen that within the state-of-the-art, these are mostly employed to generate subrogate models to approximate data obtained from multiple runs of high-fidelity complex simulations, such as those obtained from CFD or FEM analyses. These approximated models, which have a lower associated computational cost, can then be employed in earlier design stages than the ones in which the original and more computationally intensive analyses would be employed. For instance, the work of (81) trains an ANN on a set of results from CFD simulations, so as to use the network as a subrogate model in an optimisation process, instead of running the time-consuming CFD simulations at each step of the optimisation, thus greatly reducing the required computational resources. The use of this model for optimisation would place this work, according to the taxonomy adopted in chapter 2 of this thesis, within the field of preliminary design, where the potential of subsymbolic models to operate with large amounts of data and generate regression models would be leveraged.

Another use of ANNs is seen in the very recent work of (19), where a deep neural network is trained to use it as a model within the optimisation process of RPA, thus once again employing the potential of these models for regression and generation of subrogate models in preliminary design. A similar approach is followed in the research of (43) where models for the design of an unconventional V-tail layout are approximated through this viewpoint. Another work on ANNs is the one of (319), which train various models, including a neural network, on various aircraft parameters as well as on the evaluation of those designs by experts. The network then serves as a predictor model for new aircraft models which are sought to be evaluated. It should be highlighted that his latter work focuses on the conceptual design stage, as it can be evidenced also due to the type of variables that are employed, which are typical ones employed in the early design stages and in the conceptual definitions of models for this phase of the design continuum. Overall, as stated in the work of (218), the use of these types of models to develop subrogate models is viewed as one of the main applications of machine learning in aircraft design. The authors of this investigation also apply this approach for a particular case study of engine design.

Other types of subsymbolic approaches are also employed, such as genetic algorithms for optimisation of RPA. These have been used within computerised design environments for the preliminary design of RPA (61); also along with neural networks for aerodynamic design of these aircraft (123); and even in combination with data mining approaches, once again for RPA optimisation (35). There are also very recent works on the preliminary development of GenAI models for aircraft design, as seen in (320; 321). The work of (320)

is focused in the generation of 3D shapes corresponding to aircraft representations with varying aspect ratios and volume parameters. In the case of (321), the emphasis is on the integration of GenAI within optimisation processes attending to certain aircraft requirements, thus falling within the field of preliminary design.

As a final note with respect to the subsymbolic side, it should be emphasised that machine learning approaches have also been employed for the extraction of statistical relationships towards the initial sizing of RPA in the works of (45; 47). As the outputs of these works are directed towards initial sizing based on statistics, which is one of the main three topics covered in part III of the thesis, they will be commented in more detail within chapter 7.

Regarding the use of **symbolic AI approaches** in aeroplane design, and as already brought forward in advance in 4.4.1, the work related to the design environment AIDA stands out (76; 244). This is a suite of three software elements geared towards the initial sizing activities of aeroplane design. In particular, a module based on CBR compares the requirements of the applicable design case with those of similar aircraft so as to generate an initial concept. Then, a rule-based model estimates the performance of that design, guiding the user through the process to provide suggestions of configuration change. Finally, a geometric module uses the outputs from the previous elements to perform an initial graphical representation of the aircraft.

On a different but related subject, the use of symbolic approaches can also be extended to optimisation processes, as seen in the work of (101), where an expert system is proposed to guide the user through an interactive session along the different steps in the optimisation process, seeking to use to full extent the knowledge implemented in the system so as to pinpoint possible decisions to make during the workflow. The study notes that, since a great effort of the optimisation algorithm goes into evaluating at each step the function and gradient, these results should be leveraged as much as possible to ensure an effective and efficient process (101). On the field of RPA design, decision trees obtained from a database of existing aircraft were developed in the research of (35). The objective is to use these models in the selection of certain elements of the configuration, being a promising alternative for aiding the designer in making overall qualitative decisions in this regard. However, not all of the obtained decision trees are shown in the work, limiting their reuse.

Up until now, few works develop **approaches employing both symbolic and subsymbolic AI**. The investigation of (102) is among these, albeit it should be noted that it does not apply a hybrid neurosymbolic AI technique. Rather, it uses on the one hand a fuzzy logic model based on rules, and on the other hand an ANN, so as to provide a faster prediction of the wing loading and thrust-to-weight ratio design point coordinates on the matching diagram, which as seen in 2.2 is a classic conceptual design methodology. The results are very promising in both application cases developed by the authors, and they

fall within the margin of error in conceptual design, proving that two very distinct AI approaches have achieved a similar performance through different means.

It can be seen that there have been starkly different approaches for the use of AI in aeroplane design. However, a general trend can be extracted from the above-mentioned works. It would appear that symbolic AI approaches are favoured in studies more focused in the earlier stages of design, such as the one of (319) and also those concerning the development of the computerised environment AIDA (76; 244). As commented by the authors of previous works, one of the reasons for this preference is due to the capability of these models to tackle synthesis problems, which often deal with a discontinuous domain space. An example of this corresponds to the different aerodynamic layouts that can be decided for the aircraft, such as tube and wing, BWB, joined wing, tandem wing, different tail configurations, etc. On the other hand, the use of subsymbolic AI models is favoured in optimisation stages of the design continuum. Here, ANNs allow to develop subrogate models from high-fidelity simulation methods, which enable to introduce a higher accuracy in the optimisation process at a relatively low computational cost once the network has been trained (81). Furthermore, genetic algorithms have shown to perform remarkably well in optimisation processes (61).

Thereby, there appears to be certain preference towards symbolic AI approaches in the earlier design stages and towards subsymbolic AI methods when tackling the optimisation of the aircraft, which is usually done, as commented in subsection 2.1.2, in later stages such as preliminary design. This preference is not strict, however, as for instance the studies of (45; 47) have used ML approaches to derive statistical relationships that can be used in conceptual design of RPA.

Two significant gaps have been observed in relation to the main topics covered in this thesis. With respect to the use of AI models in RPA design, a comparative lack of symbolic approaches can be seen in previous works. Considering the above-mentioned preference of symbolic models in conceptual design and of subsymbolic ones in the preliminary stage, this links with the findings from chapters 2 and 4 regarding the overall higher emphasis on preliminary design approaches within the field of RPA. In addition, it is seen that, up until now, AI-based methods have seldom been employed in computerised environments for RPA, which was also observed in the survey of 4.5 regarding KE approaches. These potential areas of improvement shall be considered when substantiating in subsection 5.3.3. the selection of computerised environments and ontologies as the two main areas to be investigated within this line of research.

5.3.2. Ontologies: background, modelisation and applications

This subsection provides a theoretical background on ontologies, the main concepts related to them, and their foremost strengths and areas of application. These aspects shall be key not only when substantiating their selection as the knowledge representation technique to be studied in relation to computerised environments within subsection 5.3.3,

but also when conducting the research on the previous ontologies in areas related to aircraft design in 5.3.4 and also when proposing the main opportunities regarding their use within aircraft design packages in 5.3.5.

(a) Ontologies and relationship with AI agents

The first step to this background is to contextualise ontologies within the broader context of AI. As commented through subsection 5.1.1, an intelligent agent uses both knowledge and learning to interact with its environment and work towards accomplishing its goals. To fully leverage the potential of intelligent agents, it is key that they are encoded with accurate knowledge related to the relevant domain and/or tasks within which they will be deployed. This knowledge can be modelled using various representation paradigms, which themselves are built employing knowledge modelling components. All of these concepts and their relationships were illustrated in Figure 5-1, which will be expanded in this subsection to cover the places in which ontologies enter in this context.

Within the field of symbolic AI, it was seen that knowledge is usually codified through the use of knowledge representation languages, which have explicitly defined syntax and semantics. These characteristics make these languages readable and understandable by machines. When knowledge abstractions are implemented in these knowledge representation languages, and through the use of inference engines, computers can then perform reasoning tasks on the knowledge which has been modelled through these languages, allowing the intelligent agent to perform consistency checks and deduce new knowledge, among other possibilities.

Ontologies are one of the possible knowledge representations paradigms which can be used to model a certain domain or task of interest. They are semantic artifacts that can model declarative knowledge with different levels of formality, representing a common vocabulary containing the meaning of terms and the relationships between them within a certain field of interest (283). They are strongly related to the field of symbolic AI and represent the backbone of semantic technologies. As it will be seen later on within this subsection, ontologies are built through the use of certain modelling primitives, including the concepts and relationships mentioned above. Furthermore, they can be codified through ontology languages, which are usually themselves based on different knowledge representation languages. This allows them to be used within the KB of an intelligent agent, as well as within other types of KBS (283). Since these ontology languages have built in a certain logic with explicit semantics, this allows the agent to perform reasoning tasks on the knowledge which is modelled through them.

Considering the above, it can be seen that ontologies are not AI models themselves, rather, they fit within the notion of knowledge representation paradigms. However, taking into account the strong link between KE and AI, they can be used as a fundamental part of an intelligent agent when they are implemented in machine-readable formats which incorporate explicit semantics. This allows the computer to understand this knowledge

once it has been formally codified, which can then be leveraged in several symbolic AI approaches, such as expert systems. The concepts related to ontologies which have been introduced above, as well as the process through which they connect with intelligent agents, follows a parallel path to the associated generic concepts previously illustrated in Figure 5-1. Now, this schema is updated in Figure 5-7 to showcase the connections of ontologies with this framework, as well as the way in which they fit with the overall KE notions introduced beforehand.

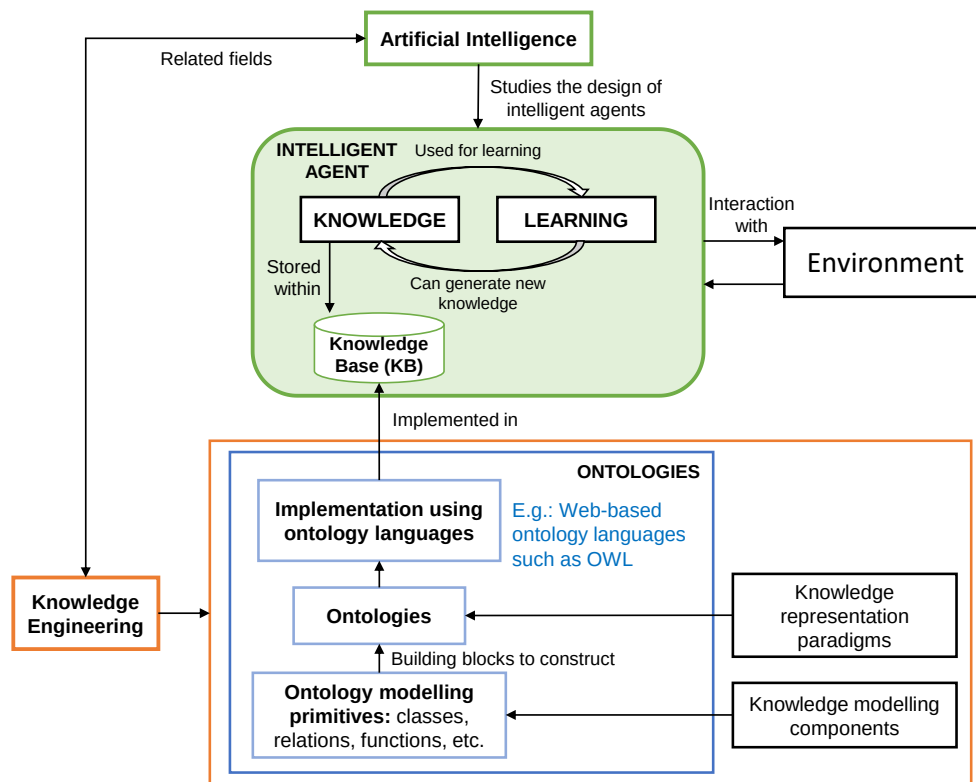


Figure 5-7. Contextualisation of ontologies within the areas of KE and AI, building on the generic schema provided beforehand in Figure 5-1.

It has been noted that ontologies present several advantages when compared to other knowledge representation paradigms, some of which make them particularly suitable for addressing the Knowledge Sharing Effort which was introduced in subsection 5.1.1 (207). This endeavour itself was directed towards solving one of the main issues of symbolic AI which is the process of knowledge acquisition. In particular, ontologies allow the developer to have a higher level of sharing and reuse than is usual in software engineering, moving from software reuse to knowledge reuse, and allowing to employ the same knowledge through heterogeneous software platforms (322). These are among the reasons why they are becoming increasingly popular in the fields of symbolic AI, knowledge modeling and sharing, the Semantic Web, and also in hybrid AI approaches such as neurosymbolic AI.

Finally, it is also noted here that, aside from the usefulness of implemented ontologies within the KB of intelligent agents, they also present several advantages by themselves as knowledge representation paradigms at a conceptualisation level. Some of these benefits shall be discussed along the present line of research.

(b) General notion of ontologies and definitions

Having contextualised ontologies within the fields of AI and KE, some further ideas related to their general characteristics are given here along with a particular example, as well as some of their main definitions in the area of computer science.

As mentioned above, the main purpose of ontologies is the representation of knowledge in an explicit and unambiguous way. This is allowed both through their structure of classes and properties, and also through the use of formal reasoning approaches, such as first order logics or description logics. A specific ontology language based on description logics is the Web Ontology Language (OWL) (323), which is broadly used in the Semantic Web and Linked Data initiatives. The structure of OWL ontologies is based on the concepts of classes and relationships (properties and attributes), and the establishment of axioms and descriptions about them. All of these are among the above-mentioned modelling primitives that can be used to build ontologies. Classes define entities such as aircraft, engine, stringer, etc., while properties establish the relation between different classes, and attributes represent the relation between classes and datatypes. It is also possible to represent taxonomic relations (also called “is-a” relations). More information on the modelling primitives which can be used to build ontologies can be found in (207).

Ontologies are used to annotate data, and both the ontologies themselves and the data are represented by means of triples. A triple is formed by a subject, a predicate and an object. In the case of the data, the subject is usually an individual that could belong to one or more classes (note that technically it is possible to have blank nodes as subjects), the predicate is a property and the object can be another individual or a data type value, such as an integer or a string. Figure 5-6 represents an example ontology which illustrates their structure, and the concepts introduced above. As seen in the figure, ontologies can be represented in the form of graphs, which can be easily expanded by incorporating new concepts and relations to the previous ones, making them scalable and flexible.

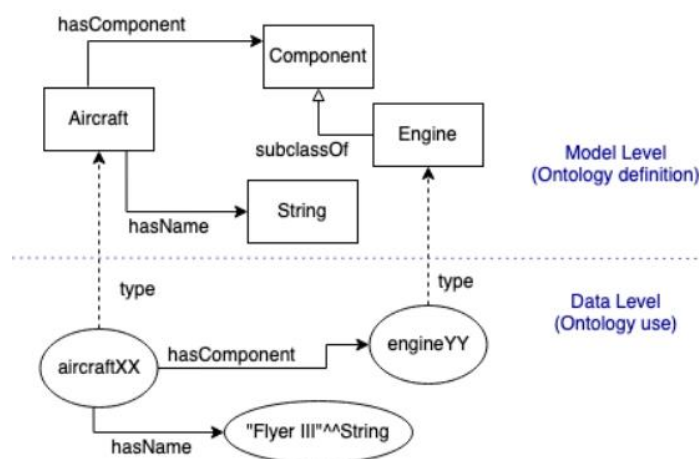


Figure 5-8. Ontology and data example, linking two classes (*Aircraft* and *Component*) through a property which represents the relation between them (*hasComponent*), the attribute name for the aircraft and the hierarchy of components (*Engine* as a subconcept of *Component*), and the use of the ontology in the data linking a particular aircraft to its engine and its name.

As with the concept of AI, there are many different definitions for computational ontologies in the open literature. One of the most quoted in the literature is the one given by Gruber, who states that: “*An ontology is an explicit specification of a conceptualization*” (324). Another key definition is the one given by Guarino and Giaretta, who state that an ontology is: “*A logical theory which gives an explicit, partial account of a conceptualization*” (325). Here, there is an emphasis in the embedded semantical capabilities of implemented ontologies. However, other definitions of ontologies do not restrict the use of this term to those semantic artifacts that are implemented in a formal logic, and they also include widely accepted collections of vocabularies that classify different aspects of reality (207; 277).

Furthermore, one of the definitions which is most quoted nowadays is that of Studer, Benjamins, and Fensel, who state that: “*An ontology is a formal, explicit specification of a shared conceptualization*” (234). Further insights on this definition are given in the Handbook of Ontologies by Staab and Studer as follows: “*‘Explicit’ refers to the fact that all elements of an ontology are explicitly defined, whereas ‘formal’ means that the ontology specification is given in a language that comes with a formal syntax and semantics, thus resulting in machine executable and machine interpretable ontology descriptions. Finally, ‘shared’ captures the aspect that an ontology is representing consensual knowledge that has been agreed on by a group of people, typically as a result of a social process*” (281). It can be seen that some of the aspects that were emphasised beforehand are a fundamental part of this last definition, such as the fact that the terms of the vocabulary contains the meaning of terms, or the emphasis on the syntax and semantics of the artificial language in which the ontology can be implemented. A more detailed account on other definitions of ontologies along with their subtleties can be found in (207; 281).

(c) Types of ontologies

Many classifications of ontologies based on differing criteria can be found within the open literature. Amongst them, the one which shall be employed with more frequency along the line of research presented in this section of the thesis is that of Lassila and McGuiness, who classified ontologies depending on their expressivity and the richness of their internal structure (326). This schema proposes a continuum of ontologies representing their changing expressivity from lightweight ontologies to heavyweight ones. On the one hand, heavyweight ontologies are considered as those who model the domain in a deeper way and provide a larger number of restrictions on semantic aspects, typically using modelling primitives such as axioms and constraints. On the other hand lightweight ontologies do not include so many modelling primitives, and might focus exclusively on concepts and properties, for instance. As mentioned beforehand, there is really a continuum of diverse types of ontologies with increasing expressivity going from the most lightweight ones to the heavyweight ones, moving on from vocabularies and glossaries, then on to taxonomies with formal is-a relationships, and finally to ontologies integrating many types of axioms and logical constraints. This classification is illustrated in Figure 5-9. Further information on it can be found in references (207; 326).

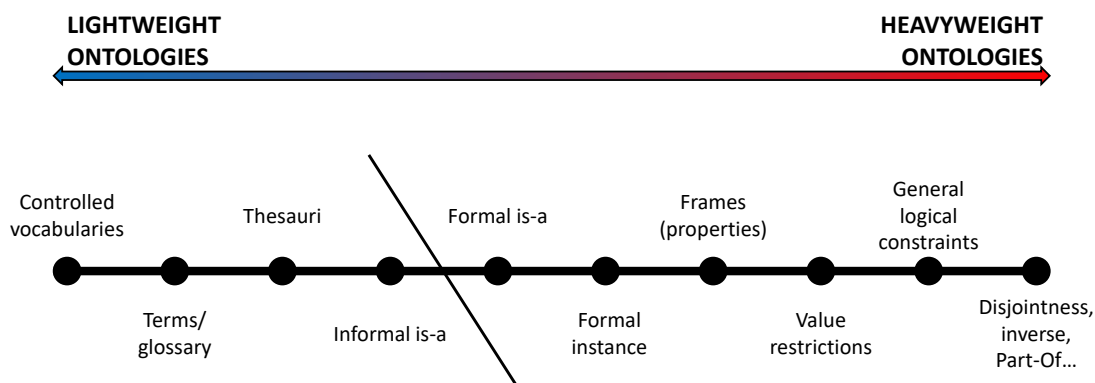


Figure 5-9. Ontology expressivity continuum from lightweight to heavyweight ones. Reproduced from (326).

There are many other classifications of ontologies. Another one of them groups these semantic artifacts depending on the subject of their conceptualisation. This categorisation moves from general or common ontologies, which represent knowledge usable across domains (such as concepts and relationships related to space, time, causality, etc.), on to other types which are more specific in nature. These include domain ontologies, which are reusable in a specific domain (aeronautical, medical, law, etc.), and task ontologies, which are more focused on terms used to solve problems. There are further classifications such as domain-task ontologies which have a narrower scope and are therefore more specialised. Ontologies which have a broader scope are more reusable, but in contrast their practical usability is lower; whereas those that are focused on a narrow scope are more usable, but have lower reusability. Parallels may be drawn between this kind of

classification and the one employed for topical areas in RPA design in chapter 2, where methods at a finer level of granularity could be reused to a higher extent within those approaches at a coarser level, but at the same time the latter ones are the ones with most practical applicability as they cover more tasks of the design process. More information on different classifications of ontologies may be found in (207; 327).

(d) Modelling of ontologies and implementation language

Albeit some of the definitions and notions of ontology commented beforehand tend to consider that ontologies are implemented in a knowledge representation language so that they are ready to be employed by computers, ontology conceptualisation can be done using representations that are independent of the knowledge representation paradigms. Under this viewpoint, knowledge artifacts that represent the main concepts and their relationships in a domain of interest, but which are not necessarily represented in artificial languages, can also be considered ontologies (277). As a matter of fact, some ontological engineering methods, which is a topic that will be briefly commented later on, recommend conducting knowledge conceptualisation using paradigms that are independent of implementation, which is then carried out at a later stage (207).

However, to fully leverage the potential of ontologies within symbolic AI approaches, they must be modelled employing knowledge representation formalisms. Ontologies can be built employing various knowledge modeling techniques, including:

- AI-based approaches, which at the same time include:
 - Knowledge representation languages (which were mentioned beforehand in subsection 5.1.1).
 - Ontology languages, which are usually built upon the aforementioned artificial languages.
- Certain techniques used in software engineering and databases, such as UML or Relational Databases (RDB).

There are crucial connections and implications between the knowledge representation paradigms that are used in ontology modelling, the knowledge modelling components (such as concepts, properties, etc.) that are to be represented through the use of the aforementioned paradigms, and the languages used to implement them (207). For instance, the use of certain knowledge representation paradigms or languages can limit the expressiveness of the formal model, and certain information, such as axioms or cardinality constraints, might not be possible to model in the formalisation process (207). This is an idea similar to that which was expressed in 5.1.1 regarding knowledge representation languages, but applied to all possible formalisms that can be used to build ontologies. Not all of the knowledge representation paradigms in general, including knowledge representation languages, have the same capability to represent different

modelling components. These topics are covered in detail within references (207) and (327). In summary, depending on the choice of formalisation paradigm employed to codify the ontology, this will impact in a significant way the ontology components that can be used at the implementation level, and also the formal semantics that are codified. Thus, the decisions made when formalising an ontology have a significant effect on the expressivity of the ontology and its capabilities.

As reported in previous research, albeit software engineering techniques such as those based on UML and RDB can be used to model ontologies, the level of richness of knowledge representation that can be achieved is often limited. Thereby, ontologies built in these ways are usually limited to those of the lightweight category (207). It is also considered that certain approaches can allow to enrich the ontology modelisation process carried out using these approaches. In spite of this, the level of formality that can be reached by employing AI-based techniques is much higher, with a much more precise restriction of the interpretation of terms, as well as the capability to model formal axioms in a flexible manner (207). Nevertheless, since the UML visual notation is remarkably extended as a modelling language in different fields of engineering, and considering as seen beforehand that ontology conceptualisation can be done through knowledge artifacts which are not necessarily represented in artificial languages, the prospects of leveraging UML during the conceptualisation activity in ontology engineering are remarkable. In this line, the Chowlk framework represents a recent effort which allows to convert digital machine-processable diagrams in UML format on to OWL ontologies (328; 329).

One of the most extended paradigms for ontology modelling is the use of ontology languages. These are often built on knowledge representation languages, which as commented in 5.1.1, can be implemented through the use of formal logics (such as first-order logics or description logics), thus allowing to leverage them in logical inference procedures and enhancing their capabilities when used to build a KB employed by a symbolic AI technique. As with other knowledge representation paradigms, the capabilities and expressiveness of ontology languages are highly dependent on the characteristics of the underlying artificial language, which have a decisive impact on the representation and inference capabilities that are supported by knowledge artifacts constructed using those languages. For example, some of the previously mentioned ontology components, such as hierarchical relations or axioms, may not be supported by languages that have a lower level of expressiveness (327).

There is a wide array of ontology languages, which are thoroughly covered in references (207) and (327). Two main groups are usually differentiated: traditional ontology languages, and web-based ontology languages. This second group has sparked particular interest due to their capability to exploit the characteristics of the Web as a data sharing platform, and they have also experienced a noteworthy development owing to their remarkable potential in the Semantic Web paradigm (207). Furthermore, they are the

ones showing the strongest potential for ontology exchange and reuse between different applications, thus improving interoperability (207). From this point moving forward, ontology languages within this second group shall be emphasised.

Most of the web-based ontology languages are based on the XML syntax, which as mentioned beforehand in chapter 4, has also been used in KBE-based modelling activities within the realm of aeroplane design environments for the development of common data formats such as CPACS and ADML. Before moving on to ontology languages themselves, two relevant web-based technologies that are built on top of XML are introduced, as they support web-based ontology languages. The Resource Description Framework (RDF) is a recommendation proposed by the World Wide Web Consortium (W3C) (330). It is a language based on triples that can be used to create metadata for describing Web resources. However, it does not have mechanisms to define the relationships between properties and concepts (207). This point is covered by the RDF Schema (RDFS), a frame-based extension to RDF that allows to describe classes and properties, and which is also a recommendation by the W3C (331). The combination of RDF and RDFS is usually labelled as RDF(S), and it allows to provide a more complete description of the data of interest, permitting among other aspects to describe the hierarchical taxonomy followed by the concepts included in the model. However, neither RDF nor RDFS are ontology languages per se, rather they are general languages to describe metadata in the Web (207). Furthermore, their expressivity would not allow to reach the level required in many ontological engineering endeavours (327).

Currently, the most extended web-based ontology language is OWL, which is intended for publishing and sharing ontologies in the Web (207), and it is also defined in a W3C recommendation (323). It is built upon RDF(S) and reuses many of its primitives, while adding more of its own. Furthermore, it is built on description logics and therefore incorporates explicit semantics, allowing to leverage the knowledge implemented in the ontologies that are implemented in OWL within symbolic AI approaches. At this point, it should be highlighted that the same ontology can be expressed using different syntaxes or serialisations. In the case of OWL, it can be notated with XML, using the triples notation of RDF, or with other formats such as the more compact Turtle serialisation. In all cases, the ontology represented through these different codifications should be the same.

Finally, with respect to ontology modelling, the topic of ontological commitments should be highlighted. This refers to the agreements on the meaning of terms and the overall hypotheses employed when modelling the abstraction of reality within the ontology. Therefore, they can be considered to be the mappings between the ontology vocabulary with the agreed conceptualisation. They allow to guarantee consistency in ontology modelling and use, but not completeness (207). This links with the aforementioned definition of Guarino and Giaretta, which referred to partial conceptualisations. This is due to the knowledge included in the logical theory employed for ontology modelling, as well as that which can be deduced through the use of inference, not seeking to cover all of

the reality of the domain which is being modelled (277). This means that the logical theory would restrict the possible meanings of terms, but they are not delimited with absolute precision, giving the parties some freedom to specialise and instantiate the ontology (207; 277).

(e) Ontological engineering and tools for building ontologies

Beforehand, many different ontologies were developed by distinct organisations through dissimilar approaches, resulting in difficulties in reuse and interoperability. One of the foremost steps in evolving the process of building ontologies from an ad-hoc endeavour to a systematic engineering task has been the development of ontology engineering methods. Ontological Engineering can be defined as *“the set of activities that concern the ontology development process, the ontology life cycle, and the methodologies, tools and languages for building ontologies”* (207). Thus, ontology engineering is not only concerned with the implementation of concepts and relationships to build an ontology, but it concerns many more facets of the process. Many different ontology engineering methodologies have emerged along the past years, with each responding to the particular needs of research and industry at the times. Some examples are METHONTOLOGY, the method of Noy and McGuinness, NeOn, and the Linked Open Terms (LOT) methodology. An overview on many methodologies for ontology engineering is conducted in references (207; 327; 332).

There are two aspects of ontology engineering which hold particular relevance within the context of this thesis. The first of these is the need for collaboration among professionals with different viewpoints. This includes ontology engineers, experts on the subject matter which is being modelled, and end users, among others. As ontologies emphasise the use of a consensual conceptualisation of the domain, considering different viewpoints in the process is extraordinary relevance (201). Furthermore, in this way the complementary strengths of each expert can be leveraged in the process. For instance, ontology engineers master the aspects related to AI, KE, and ontology development itself; whereas the experts in the field that is being modelled, such as aeronautical engineers, can provide an in depth review on the terminology, concepts, and relationships which are formalised in the ontology itself. As a matter of fact, some ontology engineering approaches have been developed considering the participation of these heterogeneous kinds of experts at different points of the process (201; 207; 332).

A second aspect worth emphasising in this investigation is the increasing trend towards ontology reuse. This links with the Knowledge Sharing Effort project mentioned beforehand in the text, which emphasised knowledge reuse to avoid building new KB from scratch each time, as this is a remarkably time consuming process (273). Following this line of thought, and as also commented above, one of the main advantages of ontologies is their interoperability and potential of reuse (322). Since ontologies emphasise modelling a domain in a consensual way, reusing previously available artifacts allows to maintain the consensus already existing in said resources (201). Furthermore, ontology

reuse allows to save time and to promote the use of best practices in the field (201). These considerations support the development of the survey on current ontologies in areas related to aircraft design that will be conducted in 5.3.4, as it does not only provide a descriptive material of the current landscape within this field, but also a baseline towards future ontology engineering endeavours so a preliminary selection can be conducted of possible semantic artifacts for reuse.

There are many tools that can aid the ontology engineer in conducting the different tasks involved in the ontology life-cycle. These include tools for building ontologies (such as Protégé), merging ontologies (with iPrompt being an example of these), or for ontology evaluation and verification (such as OOPS! and Themis). A detailed overview of such tools would be outside of the scope of this analysis, with more information being found in references (207; 281; 327; 332).

(f) Main strengths of ontologies and areas of application

Ontologies have value as knowledge artifacts themselves, as they represent the main concepts and their relationships for the domain of study. In fact, as it was commented beforehand, ontologies can be represented in a conceptual manner before their formalisation in a computer-readable format, and in fact this sequence is recommended in different ontological engineering methods (207).

Once an ontology has been implemented in a computer-readable format, because of the formalisation paradigm and the explicit semantics which are codified in its model, they present several key advantages when compared to other knowledge representation paradigms. This way, ontologies with a high level of richness of their internal structure have an added level of expressivity for knowledge representation which is not found in other knowledge representation paradigms, as they allow to represent non-hierarchical properties and axioms, amongst other aspects (207).

Moreover, the formalisation and serialisation paradigms used in ontologies also allow for easy extensibility and reusability. In particular, the use of Web technologies allows to conduct this knowledge sharing in the Web, which is nowadays the quintessential environment for data and information publishing, sharing and retrieval. Furthermore, the explicit semantics of ontologies allow to perform consistency checks on them, thereby aiding in the process of their evaluation, including checking that the knowledge that they represent has been correctly codified within them.

Authors from the field of AI have identified many areas of potential use for ontologies, including KBS in themselves, knowledge management, natural language generation and processing, and interoperability among systems, to name a few (283). In recent years, the use of ontologies for interoperability among different systems and programs has seen a noteworthy expansion, as well as their perspectives of use within cognitive agents and assistants (227). As an example, this can be seen in many practical projects spanning different areas in which ontologies built with the LOT methodology were deployed,

including Internet of Things (IoT), smart cities, health and safety, and building efficiency, among many others (332). It should be noted that, among the aforementioned areas of application, those of KBS and interoperability between systems link with two of the main trends and challenges in aircraft computerised design environments as investigated respectively in subsections 4.4.1 and 4.4.2 respectively. This further strengthens the link between the current areas of interest of aircraft design packages, and ontologies, substantiating the line of research conducted in this section.

Taking a closer look into applications related with KBS and interoperability, as identified by authors in the ontological engineering field, ontologies mainly seek to solve issues related to communication amongst people, organizations and software systems (333). These problems arise from the lack of a shared understanding or conceptualisation, since different agents might have differing viewpoints on ideas which essentially represent the same concept. For instance, the same person can be an author of a paper, the editor of a book and an organizer of an event, with each type of contribution appearing in different Websites. In order for an automatic system to evaluate and account for all three kinds of contributions, a link could be established between the person's different Web-page users accounts, which effectively represent the same entity. There are also other issues resulting from the heterogeneity of methods, languages and software tools, which hinder interoperability and resource reuse. Some particular examples of these issues were seen beforehand within this thesis, in relation to the analysis of challenges of aircraft computerised design environments, such as the lack of a common language for communication between software and organizations, or the many interfaces arising from a modular architecture of the design package.

In order to solve these problems, a unifying framework must be established, so as to define common models and conceptualisations (334). This can be achieved through ontologies, which, as commented earlier, serve as formal representations of concepts and their relations within a particular field, allowing to establish a common, shared and consensual understanding of whichever entities and concepts are considered. Ontologies can serve their purpose at different layers, being capable of representing systems, domains and even tasks (207; 234).

The foremost objectives of the line of research developed in this section are to evaluate the current landscape of ontologies in areas relate to aircraft design, as well as to propose possible uses of these semantic artifacts in aeroplane computerised design environments. As seen beforehand, ontologies can be classified in many different ways, and there are many dimensions to describe their potential application areas. Thereby, it is key to establish a classification of the main uses of ontologies from a general standpoint to use along this research. This shall aid both to group existing ontologies related to aircraft design attending to their practical envionsed uses, as well as to categorise the different areas of application of ontologies in computerised design environments.

Considering the above, the classification of ontology uses in three different areas by Uschold and Gruninger shall be used (333). An outline of the three main areas of ontology application as given by these authors is as follows:

- 1) **Improving communication between people and organizations:** since knowledge is represented in an explicit way, inconsistencies and ambiguities in concept definitions and also when establishing relationships between those concepts can be avoided. Ontologies enable shared understanding between people with differing viewpoints, which depend on their background and context. They also aid in the communication between humans and machines, employing a common conceptualisation which is both human-readable and machine-readable. The applications relative to knowledge management (234) can be classified within this area (333).
- 2) **Enabling semantic interoperability:** this area of application encompasses a series of issues which are mainly focused on machine-machine communication. They arise when different users require to exchange data coming from different software tools and from heterogeneous data sources. In this scenario, conversion of formats and models from one paradigm to another is both costly and also error prone. Ontologies can aid in improving interoperability between software systems by integrating models from different domains into a common framework. This is done by providing a wrapper to each information source which converts the data-scheme of the source to the ontology schema. In this way, ontologies can serve as an inter-lingua to represent a domain or a system of interest. This allows to link different applications and models with the same common language, solving interface problems and aiding in software interconnection (234; 333).
- 3) **Engineering systems design:** ontologies can also be used to support tasks related to the development of engineering systems themselves. These can be, for instance, software systems (281; 333), which in the context of this thesis could be a computerised environment for aircraft design. In this context, ontologies allow to represent systems (such as an aeroplane) through an explicit conceptualisation of the concepts that describe them and their interrelations. It is noted that this viewpoint can be applied at the level of the full system, such as the aeroplane, or also when considering its decomposition in various subsystems. This latter perspective would be strongly aligned with the discipline of systems engineering which was introduced in subsection 2.1.2, and as it will be seen, it currently constitutes one of the main areas of ontology development in areas related to aircraft design. It is noted that in the original classification of Uschold and Gruninger this category is named “*systems engineering*”, and is mainly focused on software systems (333). However, within the context of this thesis, it has been renamed to “engineering systems design” to avoid confusion with the discipline of systems engineering itself, which as seen above, can be one of the perspectives

applied in this area of ontology use, albeit not the only one. Some of the possible applications of ontologies within system and software engineering are: creating common models of systems (for instance, a shared model of an aeroplane including its system decomposition), specification design (ontologies can aid in this task through requirement identification in order to define explicit specifications), reusability (in order to import and export modules across different software systems, this being allowed by semantically representing the concepts which constitute the inputs and outputs of each module) and improving reliability (since the formal representation of knowledge allows to automate consistency checking), amongst others (333; 334).

Another general benefit of ontologies, which can be leveraged in different ways within the aforementioned three main application areas, is their reasoning capability. This is permitted by the formal system which defines and underpins the concepts and relations expressed in the ontology, since ontology languages such as OWL have explicit semantics, as mentioned beforehand. These capabilities allow for consistency checking, entity classification, validation, and inference, amongst others. As a particular example, inference allows to deduce new knowledge from that which is already explicitly stated, permitting to establish new relationships between concepts automatically. This is done through the application of rules such as inheritance, which states that properties of a super-class are inherited by the child-classes. Aside from the benefits arising due to their logical formalisms, ontologies can also be queried in a similar way to relational databases, in this case employing SPARQL Protocol and RDF Query Language (SPARQL) queries. Thus, as mentioned beforehand within this text, the potential of ontologies can be leveraged to a greater extent once their implementation has been carried out, allowing for them to be used within the KB of an intelligent agent.

The particular application of these advantages and areas of use shall be further analysed in next subsection 5.3.5 of this thesis, considering their use in aeroplane computerised design environments.

5.3.3. Selection of symbolic AI and ontologies for their integration in aeroplane and RPA conceptual design

As stated beforehand, the main objective of the line of research developed within this section, which is the second one of the chapter overall, is to conduct an in-depth study on the ways in which a particular AI-related approach can enhance a specific area of aircraft design application related to the scope of the thesis. As brought forward in advance beforehand, the focus shall be on the applications of ontologies (which are tightly related to symbolic AI approaches) within aircraft and RPA computerised design environments.

It has been seen within this chapter that there is a wide array of AI models, each with different characteristics, advantages, and drawbacks. The diverse features of AI techniques can be expected to make certain combinations of design applications and AI

approaches more favourable than others. Thereby, it is relevant to substantiate the decision on ontologies as the specific AI-related topic to be studied in this section, both attending to their own characteristics, as well as to the way in which they are expected to connect with the domain of aircraft computerised design environments.

For this reason, this subsection covers the reasons for the selection of the design area of computerised environments, as well as the AI-related paradigm of ontologies, for the present line of research. Aircraft design area of application

(a) Selection of computerised design environments as specific application area

The area of application that has been selected is that of aircraft computerised design environments, including those for RPA, which is a topic developed in depth within chapter 4. The reasons for choosing this topic are diverse and many have been developed in detail within preceding chapters of this thesis. These are the following:

- It was seen in chapter 2 that there is still room for improvement in computerised design environments specifically developed for RPA. Furthermore, most of the ones already available were more focused on the preliminary design stage, so the investigation of potential enhancements towards conceptual design environments through AI constitutes a relevant prospect connected to the scope of this thesis.
- As analysed and discussed in chapter 4, and more specifically in section 4.4, aircraft computerised environments are currently facing several challenges. Albeit some of them are already being tackled through other means, the investigation on the way in which AI could aid to solve some of the present issues could result in promising findings towards advancing some of these currently opened challenges.
- In spite of the main focus here being set on conceptual design, these environments can also aid in preliminary design tasks. The different scopes and methods showcased by design packages allow to investigate the use of the selected AI technique in a variety of scenarios, all within the same area of design environments.

(b) Selection of ontologies towards enhancing aircraft design environments

With respect to the selected AI-related technique, ontologies are the focus of the research to be conducted here, as it has been brought forward in advance. It should be highlighted, as commented in the previous subsection, that ontologies are not an AI technique or model themselves. However, they can serve as a knowledge representation paradigm for knowledge-based symbolic AI approaches, as expounded in the theoretical background of subsection 5.1.1. Furthermore, they also have significant value on their own as knowledge

artifacts, allowing to build a conceptual model of a domain and to construct a formal data model.

Here, the rationale supporting the selection of this topic is expounded considering the particular application area of computerised design environments. This decision shall be backed up attending to aspects pertaining to different levels of granularity. For instance, for the range of symbolic AI models, there are common characteristics that are promising for their use in aircraft conceptual design approaches that can then be integrated in design packages. At a finer level of granularity, ontologies as knowledge representation artifacts have additional advantages and their own distinctions. The reasons for the selection of ontologies towards this line of research shall be discussed based on the following dimensions:

- The characteristics of symbolic AI approaches and ontologies themselves, in contrast with other AI-related approaches, as well as their synergy with the selected design topic of application.
- The current gaps yet to be investigated in more detail within the state-of-the-art of AI application in aircraft and RPA design, as seen in subsection 5.3.1.
- Safety and explainability considerations, as seen in section 5.2, which are taken into account here due to the high interlink of aircraft design with safety aspects.

Firstly, in relation to the selection of the branch of symbolic AI, its characteristics as described in subsection 5.1.1 shall serve alongside the core topics of the thesis to substantiate the reasons for focusing on it. On the other hand, subsymbolic AI approaches have also demonstrated their usefulness in tackling aircraft design problems as seen in 5.3.1. Therefore, it is key to support why symbolic models have been the ones to be chosen here in contrast to subsymbolic ones attending to the particular area of application that has been selected as well as to the scope of the thesis.

The main focus of the doctoral research is set on the initial stages of conceptual design, as commented in chapter 1. In chapter 2 it was expounded that some of the aspects which define this phase would be the low volume of data that is managed here, its multidisciplinary nature (a trait shared with the preliminary stage, albeit in that case it is more marked), and the emphasis on main concepts and phenomena which influence the definition and evaluation of the design concept. The decisions made in this phase are based on the set of design specifications, and they often follow a reasoning process by the designer grounded on previous experience and on former design cases. The different assumptions that are made by the designer have a high impact on the models and approaches that are selected for the synthesis approach. Furthermore, qualitative aspects such as the advantages of certain layouts over others with respect to aerodynamics, structural behaviour, or stability, are also essential parts of the decision process. Therefore, certain design decisions, such as the choice of a high aspect ratio wing, have

effects on aspects related to different disciplines. In such a way, the concept of wing aspect ratio is related to the notion of vortex induced drag, where a higher aspect ratio value results in a lower drag contribution of this kind. At the same time, the structural weight would be higher when selecting a higher aspect ratio.

All of these aspects can be strongly related to the explicit knowledge and rule- or case-based nature of symbolic AI approaches. This has been demonstrated by previous works, such as those of (76; 244), where the usefulness of rule and case-based approaches were demonstrated in the development of a computerised design environment based on symbolic AI methods. The relationships expressed beforehand can be expressed through the relationships among different concepts, and it has been stated by previous authors that in the field of aircraft design it is key to be aware of the most relevant parameters and the relationships amongst them (70).

Moving on to the topic of the volume of data, the low amount of information available in the conceptual design stage with respect to the aircraft that is being designed is not expected to be sufficient to leverage the potential of subsymbolic approaches, which as seen in the state-of-the-art analysis of subsection 5.3.1, have instead seen more use for later design stages. There is, however, an exception to this argument, which is the perspective of using these subsymbolic models on a database of RPA so as to extract empirical relationships, which could then be employed for developing new RPA designs. This has been the approach followed in the previously cited works of (45; 47), where ANNs were trained on a database of RPA. However, due to the high-dimensionality of input spaces that is typical of ANNs, some challenges can arise, as a full data matrix would be required as an input for training. As it will be seen in detail within chapter 7, usually the level of detail of data available for RPAS in the open literature is low, meaning that whereas information can usually be found for variables such as *MTOM*, payload, and certain performance specifications such as endurance or cruise speed; it is much more difficult to find data on variables such as horizontal tail surface or fuselage length. When using statistical procedures to extract RPA design trends, this usually leads to a decision between either including in the data matrix many aircraft, but only considering a few variables; or considering fewer aircraft but with a larger number of variables. This dilemma shall be one of the main points of chapter 7, and is discussed in more detail there. With this, it can be seen that the use of subsymbolic AI approaches to obtain empirical relationships also showcases remarkable challenges the solution of which is not straightforward.

Another area within subsymbolic AI that could present promising prospects in relation to aircraft design would be that of GenAI, which as expounded in subsection 5.3.1, has been used in the works of (287) and (289). However, it is noted that the field of generative AI application in design is still unsettled and in its nascent stages (287; 289), thus there are yet many challenges to surmount until these models can produce as outputs practical and feasible designs. Among these, the difficulties of implementing design constraints and

feasibility checks in GenAI models have been highlighted (287), which constitutes a relevant hurdle due to the probabilistic nature of these models. This can be tackled through the introduction of validation models, but they could require significant human input (287).

Furthermore, the design representations generated by these models are often difficult to translate to practical designs or concepts which can be manufactured (287). This can be seen in the aforementioned aircraft design works (320; 321), where the generated design models present several irregularities and protuberances which are not found in feasible aircraft designs, even on unconventional and disruptive layouts, and which could potentially result in aerodynamic, structural, and stability issues. With respect to this topic, the capability of generating and representing layouts with these peculiarities is often not accompanied by analysis methodologies that can evaluate their behaviour in according to disciplines such as aerodynamics, structures, or stability and control. This gap between geometric representation and analysis capabilities was already seen in the domain of aircraft computerised design environments in section 4.2, where some design packages could generate geometries of unconventional layouts but there were certain disciplinary analyses that could not be conducted on them, as they did not have the necessary adaptations.

This is also the case in the aforementioned GenAI works, as it is seen for instance in the optimisation model presented in (321), which does not include manoeuvrability constraints, leading to some of the concepts generated by the model not complying with these requirements, as highlighted by the authors. It should be noted that, considering the very particular geometries that GenAI approaches can often produce, the development of robust and flexible analysis models which can cover the wide variety of design peculiarities that can appear can also constitute a challenging prospect. This was already one of the main difficulties in aircraft design environments for unconventional configurations, as seen in subsection 4.4.6. Even in this case, these layouts such as BWB, joined wings, and box wings present much more regularity than the outputs of generative models.

This scenario would possibly require the use of complex high-fidelity methods along with the GenAI geometry generators, which would demand very high computational resources. Another option would be the use of surrogate models, but their brittleness when separated from the training cases could still constitute a hurdle when evaluating very disruptive and irregular design concepts (291). Albeit it has been noted that the viability of GenAI producing new feasible concepts from scratch is not expected to be practicable in the short-term (335), its use to assist humans in managing complex technical documents can support the design process has been remarked (335). Overall, future research in these models is expected to focus on balancing computational efficiency with predictive accuracy (288), which is particularly critical in aircraft design.

Now, considering the particular area of computerised design environments, as commented in chapter 4, one of its main characteristics is the connection between different modules related to various disciplines to form the full design package. As commented in 4.1, there are two main lines of work towards improving these software elements. The first is related to the design and analysis models and methods themselves that are integrated in the design process. In contrast, the second one is connected to computational aspects, such as improving efficiency, interoperability, etc. With respect to this second line of work, it was seen from the findings of the design tool assessment conducted in 4.5 that there is currently a need to further improve some of these computational considerations. As mentioned beforehand, the first phases of design have a marked multidisciplinary nature, which is usually manifested in a design computer program consisting of several modules with potentially complex connections. As a matter of fact, it was seen in chapter 4 that interoperability issues were amongst the foremost current trends and challenges of aircraft computerised design environments.

Taking all the above into account, and considering the nature of ontologies as a knowledge representation paradigm with embedded explicit semantics, the advantages that they can potentially offer when using them as a common data model are worth considering. As seen in chapter 4, the use of unified data schemas has been one of the ways to tackle interoperability issues. This topic also links with KBE approaches, which was one of the main lines of work in current design environments. Overall, it was noted that aircraft design is an extremely knowledge-intensive task (95), so the use of these representations not only for interoperability, but also a way to model the domain of interest, has also been highlighted. Previous research has highlighted the need of using a common language to communicate not only the output of the design process, but also its internal process (12). Thereby, the use of ontologies for this task could present prospective advantages, as it will be developed further along this section. This would make them a noteworthy candidate for improving computational aspects related to design packages, which was one of the main two lines of work as mentioned beforehand.

As seen in previous works (101; 226), the use of expert systems in design problems, not only those related to aircraft, has given remarkable results. These agents are a type of symbolic AI, and as seen in subsection 5.1.1, one of the main elements towards their effective operation is their knowledge base, which employs a certain knowledge representation paradigm. Therefore, aside from being used as knowledge representation artifacts of the domain at hand, ontologies could also be used within the KB of symbolic AI agents which can aid the designers in conducting their tasks. These connections between ontologies and the fields of KE and AI were illustrated beforehand in Figure 5-7, and they have been particularised here for the field of computerised environments. As it has been seen, it is considered that knowledge is an essential element towards the design of rational intelligent agents that seek to maximise their effectiveness in performing a certain task. Therefore, and considering the topic of aircraft design these agents should be encoded with accurate knowledge with respect to many different aspects related to

design in order to fully leverage their potential: the different variables that define an aircraft concept, as well as the relations between them, the logic behind the process that sizes the aircraft starting from initial specifications, the way in which different analysis disciplines (aerodynamics, loads, certification, etc.) influence the geometry of the concept and therefore interact with its evolution along the design methodology, and many others. These complex connections can be modelled through the use of ontologies, which are both human and machine readable, enabling both to leverage this knowledge by humans and intelligent agents.

Now, moving on to the topic of safety concerns, the result of the aircraft design activity must be an effective and safe aircraft. This must not only be true of the final product, but also of intermediate steps along the design continuum, as it was anticipated in subsection 2.1.2, and as it will be seen with more detail within chapter 8. Furthermore, the processes, materials and results employed during the design phase can be required by the Authority as substantiating evidence during the certification process. It was already commented in section 5.2 that there is a great amount of effort in developing methods for safe and explainable AI, but the current regulatory paradigm has not yet laid out finalised guidance for subsymbolic AI trustworthiness. Furthermore, and on the topic of GenAI models, safety and explainability concerns of these generative models when used for aviation applications should also be meticulously examined, as highlighted in recent investigations of Airbus and IBM on this subject (335; 336). In view of the above, and since symbolic AI approaches, as discussed beforehand, do have better inherent transparency and explainability characteristics, it is considered that, at this point in time, the use of this type of AI models could be more beneficial when considering this dimension, so long as they can effectively tackle the task for which they are used. This line of thought would also favour the use of symbolic AI approaches for computerised design environments, which as mentioned earlier are compatible with ontologies, thereby also supporting the rationale behind their choice for this application case.

Finally, and considering a broader perspective than the field of aircraft design, it should be highlighted that the research interest in ontologies within the broad field of aerospace has been steadily increasing (337; 338). Ontologies have been proposed as standardised data models for information exchange amongst organizations (337), for safety data management and integration (339), as well as for accident and incident reporting categorization (340). Ontologies have been developed for the broad field of aviation, such as the Information Catalyst for Aviation Services (ICARUS) ontology (341), and also for specific fields such as ATM by NASA (342), as well as for space vehicle modelling, simulation and control (343). Within the aircraft design domain and related fields, ontologies have been proposed and developed for System-of-Systems design (193; 344) and for engineering design activities within product development (338). An ontology has also been developed to aid in establishing MDO architectures (246), attending to the needs of this particular field.

Moving on to aircraft design, previous authors have developed ontologies for this area focusing both on system decomposition to describe of a civil transport aircraft (345; 346) and also on the aircraft structure (199). Other studies have proposed ontologies as a means to aid in the automation of design tasks and object classification in systems design (200). The possibilities as ontologies for serving as a common conceptual representation for model integration is also expounded on in (345), where a framework is developed to allow to connect different models in aircraft conceptual design. These ontologies shall be covered in more detail along with others in the following subsection.

In view of the previous discussion, it can be seen that ontologies, both as knowledge representation artifacts themselves, and also as part of symbolic AI approaches, hold particular promise for conceptual design approaches, and in particular for computerised design environments. The heightened interest that they are experiencing in the broader field of aviation also serves to highlight their potential. Furthermore, as seen in 5.3.1, there is currently a noticeable gap in terms of AI-based approaches applied to RPA, and as it will be seen further below, this shortcoming is also seen in terms of computerised environments. These are the reasons why they have been chosen as the particular AI-related approach to be studied in this section. In subsection 5.3.4, a review is conducted of outstanding ontologies that are currently available. Then, in subsection 5.3.5, the specific opportunities that ontologies can offer to improve aircraft computerised design environments are expounded. This latter subsection also contains many more perspectives on the advantages that they can provide to design packages, this time with a more focused viewpoint in each of their possible uses.

5.3.4. Review of current ontologies in areas related to manned aircraft and RPA design

In this subsection, a review shall be conducted of previous investigations which have proposed ontologies or other semantic artifacts for aircraft design or other areas related to this topic. Research works have been included so long as they propose ideas and applications of ontologies in these fields, whether the authors have developed a particular ontology or not. This study will serve as a basis to identify the current gaps in the prospects of application of ontologies within the field of aircraft design. This analysis shall then link with subsection 5.3.5 where new areas of ontology use in the specific area of aeroplane design environments shall be proposed, accounting for the challenges and trends of design environments previously identified in section 4.4, thus suggesting ways in which ontologies can aid in solving the aforementioned hurdles.

In this context, two main areas of ontology applications can be identified, which will be analysed in this subsection: the first one relates to ontologies proposed for use in the core realm of aircraft design itself; whereas the second covers ontologies for other related fields, such as for instance, System of Systems (SoS) Design. As mentioned beforehand, ontologies have also been applied in other areas within the broader field of aviation.

However, those fields which are not directly related to the design of aeroplanes would fall out of the scope of this review.

(a) Ontology applications in the core field of aircraft design

In the area of aircraft design, various authors have employed ontologies as semantic artifacts to describe concepts which can aid in the process of aircraft design. The ontologies which have been identified in this state-of-the-art review mostly focus on system description and decomposition. For instance, this has been done by dividing the aeroplane in subcomponents (such as the wing, the engines, etc.) and linking the related concepts within the ontology hierarchically. This setup enables the application of restrictions, such as for example, that a commercial air transport aeroplane has at least two engines (345; 346). This approach allows to take advantage of several of the previously mentioned properties and capabilities of ontologies, such as property inheritance or automatic reasoning (207). Moreover, the authors of the previously mentioned investigations have also discussed the potential benefits of ontologies within the area of aircraft design, considering that this is a software and knowledge intensive area, which relies fundamentally on virtual product models (345). This connects with the findings of this thesis which were expounded in chapter 4. Moreover, the advantages related to the use of ontologies that previous authors have identified are aligned with the general strengths and areas of ontology application as commented in subsection 5.3.2 (333), that is: avoiding ambiguities, allowing for semantic interoperability, and taking advantage of their inference and reasoning capabilities.

The authors of the AIRCRAFT ontology developed in (345; 346) acknowledge the current difficulties in aircraft design with respect to module interoperability. This is aligned with one of the main challenges in computerised design environments as seen within this thesis in section 4.4. The authors of the aforementioned ontology highlight that, often, several software components which are being employed in parallel within early design phases refer to a same concept in different ways, and this particularly occurs in the areas where different analyses overlap. Taking into account that the disciplines involved in the design of an aircraft are tightly coupled, as mentioned earlier in this thesis, it can happen that several model elements across domains actually represent the same entity. Therefore, the authors propose the AIRCRAFT ontology as a means to solve these model inconsistencies by employing a common semantic model as a reference, assuring consistency amongst the different modules (346). This would be aligned with the first area of application of ontologies commented in 5.3.2. By mapping the different model elements to the reference ontology during the design process, it can be used as a common data model which can identify, through reasoning, the points in which inconsistencies occur (345), therefore also contributing to semantic interoperability. These capabilities represent the second and third areas of application mentioned earlier, since the ontology also serves as a system representation formalism and can check its validity.

In contrast to other ontology-related works covered by this survey, the research conducted by these authors has also documented some aspects related to the ontology engineering process used to conceptualise the AIRCRAFT ontology. In particular, the NeOn methodology for ontology engineering – covered in reference (201) – was employed in this research. The authors formulate the different competency questions which serve as a basis for the ontology engineering process, and discuss the results of applying the NeOn methodology to their particular ontology development scenario (346). Non-ontological resources employed within the application of the NeOn methodology for ontology development in this particular case have included system-based decompositions obtained from aircraft computerised design environments, including the Pacelab Aircraft Preliminary Design (APD) suite which was one of the packages studied in chapter 4. The parameters describing the aircraft in the decompositions consulted as sources of information towards the development of the AIRCRAFT ontology were organized hierarchically (346). This represents a relevant synergy with design packages such as those studied in chapter 4, since they can be used as a knowledge source which, as shown, can be conceptualised in the form of an ontology. The resulting AIRCRAFT ontology, which is publicly available (347), includes a system decomposition of an air transport aircraft similar to the Airbus A320, as well as parameters that describe the different subcomponents, such as the Aspect Ratio (AR) of the wing and tailplanes (347). Therefore, this ontology serves as a common data model that represents geometrically and at sub-component level the aircraft which is being designed.

The AIRCRAFT ontology was utilized as a basis for a set of three ontologies which were developed in a subsequent investigation (348). In this case, the objective was to employ ontologies as tools to model corporate knowledge, so as to enable to search through it by querying, therefore being related to the knowledge management area. Consequently, these ontologies can be classified within the first and third areas of application mentioned in subsection 5.3.2, since they serve both to improve human-machine communication and are also employed in the development of a search and indexing system. The authors of the referenced research acknowledge the importance of such semantic search capabilities for aeronautical engineering projects in their early stages, which is precisely the focus of this thesis. One of the main topics of the aforementioned research (348) is the integration of these three ontologies which represent different areas of an aerospace project domain, but that at times may overlap: the Documentation Ontology (DocO), the Model Ontology (ModO) and the Design Ontology (DesO), each of them with differing ontological commitments. All three ontologies, and particularly ModO and DesO, include concepts employed in the sizing and design of aircraft (348), therefore being within the scope of the review presented here. Furthermore, the DesO ontology builds upon the AIRCRAFT ontology commented before, constituting an example of ontology reuse.

The Aircraft Structure Ontology (199) has a similar objective to the aforementioned AIRCRAFT ontology, in that it seeks to aid in the development of a digital model representing the aircraft and its subcomponents. In this case the approach is slightly

different, as the ontology is developed through a classification based on the Air Transportation Association (ATA) codes, which serve as a standardised reference for aircraft system decomposition. The ontology development process also employed term extraction and relation through natural language processing from aeronautical technical documents describing the entity of interest (199). The resulting ontology organizes in a hierarchical manner the components and subcomponents of the aircraft, including its wing, tailplane, engine and undercarriage, amongst others. Some portions of the resulting ontology are shown in the article written by the authors (199). Albeit the applications of the ontology have yet to be explored, the authors have proposed the areas of automatic translation, information retrieval and aircraft maintenance and design, albeit amongst these areas, the ontology would be most focused in the support of aircraft maintenance management systems (199). This would mean that it is can also be classified within the first and third areas, due to its system representation and its intended use for information retrieval (human-machine communication and knowledge management).

Another ontological artifact has been developed in (200), the objective of which is to classify the different objects involved in the conceptual design process. An ontology development approach based on natural language processing is proposed, and portions of the results are shown. In this case, the resulting ontology is focused on aircraft engine classification. It must be noted that the level of expressivity of the ontology would be that of a dictionary of terms, or a thesaurus-alike classification, due to the modelling of 'isSubclassOf' relations and 'isPartOf' properties being the same. The purpose of the ontology is focused on the description and categorization of engine concepts (200).

There have been other research works tightly related to the area of aircraft design in which authors have employed methods with certain similarity to ontologies, such as object-oriented programming (72), frame-based systems (221), and also UML diagrams, to represent concepts and their connections within a KBE system for aircraft design (12). This latter approach also has the objective of expressing the knowledge of the design domain through nodes and relations (12). Interest is also arising on Semantic Web technologies for their future application in establishing common system representations (72) as well as to enhance central data models such as CPACS in future revisions (221). These authors acknowledge that there is still much room for research within the field of ontology/Semantic Web applications in aircraft design (72; 221) .

(b) Ontology applications in other areas related to aircraft design

Other authors have developed ontologies in areas which, albeit not strictly focused on aircraft design, do involve knowledge and models which can be applicable to the design process of an aircraft. As seen in the ontological engineering field (201; 207), one of the main steps in an ontology design process is ontology reuse, which seeks to leverage knowledge which has already been agreed, formalised, and implemented in previous ontologies when creating new ones. Therefore, in an ontology development process it is also key to consider ontologies developed in fields related to the one of interest, as well

as more general ontologies, to evaluate possible reuse of ontologies. This is one of the main reasons for including the following semantic artifacts within this review.

In the research work of (349), a framework for developing engineering design ontologies specifically within the aerospace industry is developed, proposing an ontology engineering methodology particularly focused in this field, the objectives of which are to strengthen modularity and reuse of ontologies. Precisely, the authors highlight the modular aspect of design, which arises from the complexity and heterogeneity of the process, as it has been mentioned previously within this thesis. The authors of the cited research also acknowledge that most ontologies within the aerospace industry were focused on manufacturing rather than on design (349). The main objective of the ontologies developed within their proposed framework would be to support knowledge management processes, such as the access to relevant knowledge on Web-based platforms in order to expedite the design procedures. Since this use of ontologies is geared towards engineering design, and knowledge management can be a valuable asset in aeroplane initial design procedures (12; 72; 232) as mentioned in subsection 4.4.1, the cited investigation (349) falls within the scope of this review. However, it has been included within this subsection instead of in the former one since it is not specifically focused on aircraft design, albeit the authors explain that for products which are related (for example, subcomponents of a higher-level element, such as an engine), the high-level concepts of the product design ontologies are expected to be similar, while the lower and more specific level shall be different (349). This could allow, for instance, to reuse the top-level of ontologies developed within this framework for the case study of aircraft design. Aside from presenting their methodology for ontology engineering, various example ontologies are presented, with the main overarching theme being the design of combustor casings. For instance, the combustor product ontology describes a hierarchical breakdown of this engine component in its sub-components. Albeit the upper-levels of the ontologies are presented in the paper, the lower-level concepts are not available.

The research conducted in (338) is focused on SoS engineering. This discipline is tightly related to that of Systems Engineering, which was outlined in subsection 2.1.2. The authors acknowledge that there is room for improvement in SoS design methodologies, such as for instance in the development of more guidelines to tackle these endeavours. SoS design is characterized by considering a global system composed of various constituent systems, each of them having its own design space. All systems in combination work together in a larger-scale design space in order to provide a joint answer to the customer's requirements, taking into account their dynamic nature. An example of this kind of system could be a swarm of RPAS operating jointly with a series of boats for a SAR scenario, in which the global system is formed by all vehicles and the scenario itself. In the publication (338), the authors identify various methodologies and techniques which could aid to put into practice their vision of SoS design framework. These include semantic ontologies and ontologies as paradigms which can aid to establish a common language to describe systems and connect various stages of the design process. This

concept is also aligned with current trends of aeroplane design as seen in section 4.4, particularly with interoperability, where central data models which establish a common language were seen, such as CPACS; and with multi-fidelity analyses, since they also seek to connect different stages of the design process, albeit in the case of the cited SoS work this is not done in the dimension of lower and higher fidelity analyses, but in the way of connecting the global design space analysis to that of each constituent system. The objective of the ontologies developed in this context would be to serve as a representation of the inputs to an SoS design procedure, which links with the dimension of “specification design” as seen within the third area of application of ontologies commented in subsection 5.3.2.

Albeit a specific ontology was not presented in the previous work the authors further advanced their research by developing and applying an ontology to a case study in (193). In their investigation, the authors sought to perform an exploration at the highest level of the SoS design, that is, the analysis of the capabilities of the full system composed of several constituent systems. This exploration was done through the application of inference capabilities of an ontology describing both the scenario (a SAR mission at sea) and the capabilities of several constituent systems. The optimal combination of these constituent systems is sought so as to provide the optimum capabilities to the whole system, attending to the needs of the mission. In this way, capabilities which are not attainable through a single constituent system can be obtained by means of the collaboration amongst different ones. The development of the ontology was done attending to the current needs of SoS engineering (193). Excerpts of the SAR ontology, which is implemented in the OWL language using Protégé, are presented in their paper, albeit the full ontology is not publicly available.

Ontologies have also been applied in the field of optimisation, which, as mentioned in 2.1.2 is a fundamental part of the preliminary design process. In the work of (246), Semantic Web technologies, and in particular ontologies, are proposed to model and describe an optimisation process, following a KBE approach. They serve both as data model and data structure to represent MDO architectures, providing templates which can be used for automatic formalisation and integration. The process also employs semantic querying and reasoning to aid the user in defining the optimal architecture for the MDO process. The ontology also seeks to define dependencies amongst the MDO blocks, therefore also contributing to interoperability. It should be noted that the ontology does not describe aeronautical products in itself, however it can be used for their optimisation, as demonstrated in the research (246). This is in a similar vein to other studies which have also used expert systems based on KBE to aid in decision-making during optimisation processes (101; 350), albeit these were not directly in relation with aviation. This process has been usually done by establishing a series of rules in the system which can then recommend a certain optimisation algorithm, as well as ranges for the input variables, amongst other assets.

Since this thesis is focused on RPA, references focused on this type of aircraft have also been sought. A previous study (351) has developed a glossary to describe the different elements which can serve to describe the trajectory of a mission path of RPA. This approach also assigns certain properties to the points and segments which form the route in order to provide a complete description of the performance expected from the aircraft at every point of the path. The authors propose this ontological artifact to avoid ambiguities and achieve a unifying definition of RPAS missions, in order to describe the widest range possible of undertakings (351). Another study, albeit mainly focused on the assignment of sensors to missions (352), also considers RPAS as part of the approach, since they are the aerial platforms to be equipped with the sensors. As mentioned in chapter 1, RPAS present a wide variety of possible missions, and often distinct operations are conducted with diverse types of sensors, as some of them are more linked with certain missions than others, as seen in the data compiled by (36). In the case of the aforementioned research (352), ontologies describing the mission, sensors and platforms have been developed. The objective of these ontologies is to describe the problem at hand, in order to then apply semantic reasoning, allowing the system to recommend types of sensors and platforms for the mission. Then, a search through a database containing instances of these sensors and platforms is conducted attending to constraints based on the results of the recommendation. This allows to achieve an approach for automatic platform and sensor allocation (352). This ontology would fall within the scope of the review presented here since one of the first steps in the aircraft design process is the definition of requirements, as seen in Figure 1-1 and discussed in subsection 2.1.2, where this payload selection method would fit.

As mentioned in subsection 5.3.3, there are other ontologies which have been developed within the aerospace field, albeit in most of these cases, they may be considered to be further away from the area of aircraft design. Particularly, an ontology at generic domain-level is being developed for the broad aviation sector, named ICARUS (341), which seeks to aid in data management by linking data across different domains through a common data model expressed by the ontology. Even though ontologies such as this one are not directly related with aircraft design, they could also be considered for reuse in this domain when building an ontology, so as to include some of their classes and properties.

(c) Summary and ontology areas of application

Having analysed the various references found in the open literature covering ontologies in relation to aircraft design, a brief summary has been compiled in Table 5-2. It categorises the references with respect to their focus from an aircraft design viewpoint, as well as regarding the main areas of application of ontologies outlined in subsection 5.3.2.

Table 5-2. Summary of references covering the topic of ontology engineering for aeroplane design and related areas, organized by aeronautical field of application, including those related specifically to RPA design, and also sorted by each of the previously identified ontology fields of application. The citations are accompanied, where applicable, with the given names of the ontologies developed in the research or related to it.

	1. Communication	2. Semantic interoperability	3. Engineering system design
Aeroplane design	• AIRCRAFT ontology (345; 346) • DocO, ModO, DesO (348) • Aircraft structure ontology (199) • Aircraft engine ontology (200)	• AIRCRAFT ontology (345; 346)	• AIRCRAFT ontology (345; 346) • DocO, ModO, DesO (348) • Aircraft structure ontology (199)
Areas related to aeroplane design	• (338; 349) (various ontologies) • SAR ontology (193) • MDO ontology (246)	• (338) • SAR ontology (193) • MDO ontology (246)	• (338; 349) (various ontologies) • SAR ontology (193) • MDO ontology (246)
RPA design	NONE	NONE	NONE
Areas related to RPA design	• Unmanned Aerial Vehicle mission ontology (351)	NONE	• Sensor assignment ontology (352)

As it can be seen, the previous works of ontology applications in the field of aircraft design which have been reviewed are strongly aligned with the three main areas of ontology use as commented in subsection 5.3.2. The main focus of previous research has been on the advantages resulting from having a common definition of the concepts and systems involved in the design process, as well as on the various engineering system design applications of ontologies. Furthermore, the trend of ontologies being used for common data models fits with the software interoperability challenge for computerised design environments highlighted in subsection 4.4.2. As mentioned there, in order to achieve an adequate interoperability, it is necessary to both have a common data model and to establish communication amongst software elements through it. In view of Table 5-2, the semantic interoperability field in ontology applications within areas related to aircraft design still has room for development, and the advances that could result through a more extended use of ontologies as common data models would constitute a promising step forward. With respect to the reasoning capabilities of ontologies, their applications have been diverse. Some references have employed them for model consistency checking (345; 346) and others for decision aid in selecting different solutions (193; 246; 352). Querying the ontologies for retrieval of relevant information has also been one of the main applications encountered in this review, such as in the works of (348; 349). Depending on the purpose of the queries, this approach can be included either within the communication area or the engineering system design one.

It should be noted that, as of now, the analysed ontologies have not yet been applied to computerised design environments. Albeit in the case of the AIRCRAFT ontology as seen beforehand the system-based decompositions of previous design packages were used as a source of information to model the ontology, it has not been applied to design packages of this kind, thus the specific necessities of design packages regarding ontology integration remain to be addressed. Furthermore, there is still room for development of ontologies geared towards the design process of RPA, with its different steps and methodologies. A further classification of the references that have been analysed here can be seen in Figure 5-10, where they have been located in the different topical areas related to aircraft and RPA design. As it can be seen, there are various ontologies in the broad areas related to aircraft design (System of Systems design, ontologies for aeronautical engineering design, and ontologies relative to specific missions), and there are also some ontologies in the more specific area of aeroplane design. A couple of references can also be included within the broad area related to RPA design. However, the more specific area of computerised design environments, as well as the one corresponding to RPA design, and also the cross-area for RPA computerised design environments, remain as of yet to be explored from the viewpoint of ontology development and their applications. Furthermore, from all of the ontologies that have been analysed in this survey, only the AIRCRAFT ontology is fully and publicly available in a knowledge representation language. Ontology availability is fundamental for ontological reuse, which is a key step within ontological engineering processes (207), and also for establishing connections amongst different semantic artifacts. Therefore, it is clear that there is also room for improvement in this regard within the field of aeroplane design ontologies.

However, even if these ontologies have not been designed for their specific application in computerised design environments, some of them could be reused when developing an ontology geared towards design packages. In this vein, some examples are commented in this paragraph. Firstly, albeit the focus of the FunGramKB ontology is not so much on design but on maintenance, seeking to describe the different subcomponents to serve as support to aircraft maintenance management systems (199), many component concepts which are represented in it are also involved in the design process. The DocO, ModO and DesO ontologies are tailored towards information management (348), which is also useful for the conceptual design process, for instance, to search for relevant information, as highlighted by the authors themselves. The SAR ontology is focused on a very specific mission and is more cantered in subsystem selection (193), however, many of its concepts could be reused to represent these kinds of missions for requirement specification at the initial stages of the design process. The capabilities of the MDO ontology could be leveraged during the optimisation process at a preliminary design stage, albeit, as mentioned earlier, it does not describe the product of design process itself or the disciplines involved, being focused on the optimisation structure and algorithms (246). Finally, the AIRCRAFT ontology could be employed for system and component definition and serve as a common model for module communication, as it was proposed by its developers in (345; 346).

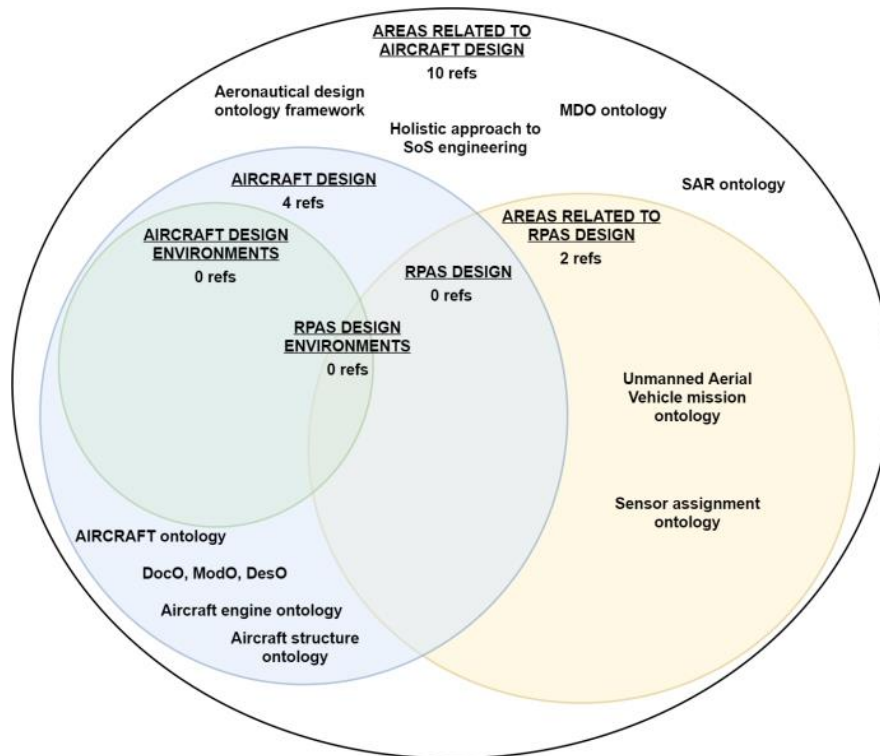


Figure 5-10. References relative to ontologies for aeroplane design located within different related topical areas. RPAS have been considered as a particular scenario of aircraft design, accounting for the fact that the scope of this investigation is set on fixed-wing RPAS.

As it has been mentioned, one of the key assets of ontologies is their reuse capability. Albeit many of the previously analysed ontologies have not been developed towards the needs of aeroplane computerised design environments, the concepts which they describe and the properties that link those concepts can be reused for an ontology with a different objective but sharing the same domain and concepts. Therefore, it can be considered that the review conducted here can also be leveraged in future ontology engineering efforts as an initial compilation of possible ontologies for reuse, being an added benefit of this contribution.

However, even with the potential reuse of existing ontologies commented above, there would still be some key gaps towards leveraging their potential towards future applications in aeroplane computerised design environments. Firstly, in view of the review conducted above of ontologies pertaining to areas related to aeroplane design, the opportunity of developing a domain ontology for aircraft design, as well as task ontologies for certain design procedures, remain open, since the AIRCRAFT ontology and its derivatives have been conceived essentially as a representation of the system itself, rather than a conceptualisation of the field of initial design or its activities. Furthermore, some of the needs of computerised design environments which were expounded on chapter 4, particularly those aspects which could be enhanced through the use of ontologies considering the capabilities of these semantic artifacts, would, as of now, still remain unattended. In order for ontologies to be specifically tailored to tackle some these

challenges, the first step is to clearly identify these issues, which include hurdles related to the design software workflow, interoperability and data representation, amongst others, so as to then develop the ontologies with these aspects in mind. This is the main reason why, in this research, firstly the main challenges of design packages have been identified and discussed, and then the potential advantages of ontologies have been studied, so as to now, moving on to subsection 5.3.5, match the opportunities and capabilities that ontologies offer with the challenges to be solved in computerised design environments.

5.3.5. Opportunities and challenges of ontology applications in aeroplane computerised design environments

As it was seen in the previous section, the ontologies that have been identified within areas that are adjacent to aircraft design showcase the interest in their application in aeronautical design. Moreover, previous authors have acknowledged that the multidisciplinary and heterogeneous nature of aircraft design can greatly benefit from ontologies and Semantic Web technologies (72; 346). Still, ontology design and application within the area of aircraft computerised design environments has yet to be studied in detail and demonstrated.

Considering the above, it is sought to conduct in this subsection a prospective analysis on the opportunities and challenges of ontologies within this area. This study shall be based on two previous analyses conducted within this thesis, with these being the main trends and challenges of aircraft computerised environments which were analysed in section 4.4, as well as in the findings of the preceding subsection 5.3.4 with respect to previous efforts related to ontology development and proposal in fields related to manned aeroplane and RPA design. It can be considered that a more thorough study on how the strengths of ontologies can match the current needs of aeroplane design packages, so as to seek potential opportunities of ontological applications that can aid in surmounting some of the current issues of these packages, could aid to further develop this combined area of research. Furthermore, since the potential advantages that ontologies can provide to the area of aircraft computerised environments has seldom been studied in detail beforehand, particularly when considering how ontologies could aid in surmounting the specific challenges of this field, the analysis provided here can contribute novel insights on the opportunities that can be leveraged with the use of ontologies in these packages, thus covering on the two objectives planned at the onset of this chapter.

This way, the matching between design package needs and ontology capabilities shall provide a series of prospective areas for ontology application within aeroplane computerised design environments. Following this process, the proposal of ontology applications shall be done attending to the necessities of the particular research area of interest, as previous authors have developed in their other fields (193; 246; 344). These possible implementations will also be compared with the current methods and

technologies employed in design environments, in order to discuss the added value that ontologies can contribute to these design packages. After evaluating the potential benefits of ontologies in computerised design environments, the foremost challenges towards ontology application in this area shall be commented.

(a) Opportunities: main prospective applications of ontologies within aeroplane computerised environments

The first step in order to identify the opportunities of application of ontologies in aeroplane computerised design environments is to match the current needs and challenges of these design packages with the strengths and general areas of application of ontologies. This matching is provided in Table 5-3, and in the intersection of each design package challenge with each main advantage of ontologies, different potential uses of ontologies are identified.

The potential distinct applications of ontologies proposed in Table 5-3 have been classified, and each of these main potential use areas shall be discussed in the subsections which follow below. It must be noted that, albeit a distinction has been made amongst the identified applications, in reality most are interconnected (as it was the case with the design package challenges themselves, as seen in section 4.4, and the ontology strengths and application areas, as seen in subsection 5.3.4), and the boundaries between these categories can in certain cases be fuzzy. This is also the reason for many of the identified applications appearing in various cells simultaneously. For instance, the development of an ontology to describe the system of an aeroplane serves both as a common model for communication and also as an engineering system design benefit, since the ontology is geared towards representing a system in an unambiguous and consensual way. Therefore, many applications can fit simultaneously in different columns corresponding to main ontology strengths. In the same way, the solutions from the aeroplane design standpoint can also be located in different trends seen in this software, which correspond to the rows. For example, a common parametric format would serve both for software interoperability, as well as a KBE tool which represents knowledge about the sizing of a particular element. These nuances and connections shall be highlighted within the discussion provided below. Furthermore, taking into consideration the aforementioned overlaps, the first category which has been defined corresponds to general ontology applications and potential advantages in aeroplane computerised environments, with some of the other categories, which are more specific, being particular applications of these general advantages in specific areas.

The following sub-sections discuss the different ontology application categories shown in Table 5-3, as well as the added value that ontologies would constitute when compared to current – non-ontological - approaches, which were already commented for each of the trends of computational environments in section 4.4.

Table 5-3. Matching of computerised design environments main trends and challenges with the main strengths and areas of application of ontologies. Please note that the rows correspond to the challenges of design packages as analysed in section 4.4, and the columns to the fields of application of ontologies as seen in subsection 5.3.4. The content of each cell reflects a possible area of ontology applications, each of which shall be discussed in the main text, organized by their numbering as presented here. Where references are cited, they correspond to works that have investigated the related applications before.

	Communication	Semantic Interoperability	Engineering system design
General Uses	1. General ontology applications in communication, interoperability, and systems engineering		
	2a. Ontology as common model	2b. Ontology as a common language	System representation Consistency checking (345; 346) *
Knowledge Based Engineering	3. Parametric models 4. Data and knowledge management (348; 349)	3. Parametric models	3. Parametric models
Software interoperability		2b. Ontology as a common language	
Design in collaborative environments	1a. Ontology as a common model	2b. Ontology as a common language	
Framework extensibility	5. Extensible (graph) model		
Multi-fidelity analyses		5. Extensible (graph) model 2b. Ontology as a common language	7. Analysis selection and adaptation
Unconventional configurations	6a. Modelling unconventional configurations	2b. Ontology as a common language	6a. Modelling unconventional configurations 7. Analysis selection and adaptation
Remotely Piloted Aircraft Systems	6b. Modelling RPAS	2b. Ontology as a common language	6b. Modelling RPAS 7. Analysis selection and adaptation

*: these applications can be considered as particular cases of that of “1. General ontology applications in communication, interoperability and systems engineering”, as commented in the corresponding subsection.

(a.1) General ontology applications in communication, interoperability and systems engineering

Authors both from the artificial intelligence and computer science field (230; 333; 334; 353) as well as from the aeronautical area (221; 337) have recognized that there are many barriers to overcome in the area of software engineering to establish an effective communication between humans, machines and organizations. Particularly, in the specific area of study in this research, which are computerised design environments, this issue is further complicated due to the notable heterogeneity of software components and modules which have to be considered (as mentioned in subsection 4.4.2) and the individuals from the different organizations, as well as the complex nature of the organizations themselves (as commented in subsection 4.4.3). Each of the involved agents has their particular background, preferences and methodologies. If these barriers cannot be overcome, the aircraft design process becomes inefficient and error prone.

Taking into account the main concept of ontologies introduced in subsection 5.3.2 their use as a shared explicit representation of knowledge is invaluable in this context. Having a common definition of the system, the design process and even of the methodologies involved is expected to aid to solve the aforementioned communication issues. The ontology constitutes a shared understanding of the domain (for instance, an ontology representing the design process with its different stages and dependencies) and of the system which is being developed (in this case, the aeroplane and its diverse subcomponents). The communication between machines or programs (interoperability) is also one of their assets. Previous authors have already advocated that the use of ontologies in scenarios with these characteristics (heterogeneity of software, concepts, knowledge and agents) serves as a way of resolving the aforementioned issues (337; 334).

With respect to **communication**, the common conceptualisation expressed with an ontology serves as a reference knowledge representation of the domain, system or task at hand. If the entity represented within the ontology is a system, as it was the case with the AIRCRAFT ontology (345), then this representation would also fall within the engineering systems design category. This common model aids to establish a common definition for the concepts represented in the ontology, as well as for the relations between them. This helps to reduce ambiguities and differing assumptions, reaching agreements over potentially ambiguous terms, and establishing an interlingua correspondence for the same underlying concepts (333). Overlaps between classes which represent the same concept can be established as synonyms, to define that they represent the same idea, and therefore solve this issue. For instance, the definitions of “Maximum Take-Off Weight”, “All-Up Weight” and “Gross Take-Off Weight” might be considered to refer to the same concept. With ontologies, this can be annotated and made explicit in the model.

The dependencies and assumptions which are inherent to any model can also be represented explicitly with an ontology. For instance, the aerodynamic model does not require the internal structure of the wing, but for structural analysis it would be a

required input. Another example would be the polar curve, since in initial performance calculations a non-trimmed drag polar is frequently used, without considering the lift of the horizontal tail. However, for stability and control estimations, it is necessary to consider the forces and moments originating at the tailplanes. Making all of these assumptions explicit allows to improve communication, avoiding errors and preventing differing assumptions and incongruities in the design tasks when the aforementioned aspects are not explicitly stated in the documentation. This application can also be considered within the engineering systems design category, since it seeks to achieve a complete definition of the modelled system.

Aside from the assumptions, other information which can be stored within ontologies are metadata referring to the origin of the compiled information. This allows to keep track of where the data comes from, which is notably useful in the case of conceptual design, as databases are often compiled and employed here to extract statistical relationships. Often, some outliers can be detected through the provenance of the information, which might correspond to sources with a lower level of fidelity. Furthermore, in the design process often the same parameter can be obtained through various means. For instance, the wing surface can be obtained in some cases through the selection of the design point which represents the aircraft in a matching diagram (7; 8) or from a statistical correlation which represents the wing loading parameter (38; 104). Keeping track of this information aids in maintaining the consistency of the model and of the steps of the design procedure, avoiding contradictory results and overlaps. Provenance has also been implemented in formats such as XML (221; 240) in languages for aircraft design.

Other communication advantages stated by previous authors in the computer science field are those related to the definition of networks of relationships (333). In the case of computerised design environments, the variables defining the aeroplane are highly interlinked. For instance, the Aspect Ratio of the wing influences both the aerodynamic calculations (where a large aspect ratio is beneficial in reducing vortex-induced drag), and the structural ones (where, in contrast, high values of this variable result in larger bending moments at the wing union with the fuselage). All of the dependencies amongst the variables can be represented, to keep track about what is linked and evaluate these relationships to see how changes in the system can propagate.

In the area of **interoperability**, using the ontology as a common language has several benefits in connecting different software tools. This area, as expounded in subsection 5.3.2, is geared towards machine-machine understanding. By standardising terminology, different computer resources, which in this case would be the various modules and external software involved, can be connected more easily, since the same concept has an explicit denomination. Another implementation possibility is using the ontology as a common language (or interlingua) to support translation between different formats and representations (333). In this scenario, as it was the case with CPACS and other common data formats (as seen in subsection 4.4.1), the ontology can be used as the central node,

which connects to the different tools employed, represented by modules and external software. Following a similar approach to the comparison among the number of required interfaces in a computerised environment which was expounded in 4.4.2, the configuration proposed here would reduce the number of translators required from the order of N^2 to N , where N is the number of components. In this way, the translators would only require translating from each native ontology to the common reference ontology (333).

The second relevant contribution of ontologies in the area of interoperability would consist in the integration of models of different domains into a coherent framework (333). Interoperability can be established both within the software (internal interoperability) and also with external components (external interoperability). In the first case, this interoperability can be established to solve the interfacing issue described above. It might also be necessary if there are some legacy systems under the control of the organization, adding some difficulty (333). Hypothetically, if the legacy system was defined by an ontology and another ontology was established for the new software, the network of concepts could be searched for those of the legacy system which could be reusable, and therefore, in this way, aid in recovering the capabilities of the software where necessary. Internal interoperability can also be fostered through defining elements in different modules which represent the same concept. This could be used in the case example of the Aspect Ratio mentioned earlier, where this variable, represented in each domain (aerodynamics and structure) can be related with a synonym property, therefore establishing that they represent the same concept. In this way, the properties of the variable in one domain shall become interlinked with the ones in the other domain.

With respect to the benefits in the area of **engineering system design**, once again, the common representation of the system employing explicit criteria aids in its understanding and analysis. Furthermore, the flexibility of ontologies can allow to make simultaneous decompositions of the system attending to various criteria. As commented by previous authors, both a system and a geometric decomposition are viable alternatives for this task (72). In the end, the decomposition should arrive to the same group of elements. These different hierarchical classifications can be represented through an ontology.

As mentioned in subsection 5.3.2 within the broad category of engineering system design benefits, there are many possible applications for ontologies. These have been evaluated by previous authors in the computer science field (333; 334). The foremost benefit would be having a model of the system which represents the relationships between its different subsystem explicitly and unambiguously, serving the ontological model as a systems engineering model, in this case, of the aeroplane, including its different decompositions. Another of these advantages consists in software reusability. Since there is a common and formal encoding of the relevant entities and relationships in the domain of interest, this formal representation can be a reusable or shared component in the design environment

(333). For example, a module which calculates the aerodynamic characteristics of a wing based on an input geometry and flight condition could be reused by another design environment as long as the inputs representing the same concepts are provided. This can be even coupled with a translator from the native language of the organization to the ontology of the module, which ensures that the right inputs are provided. This is aimed at solving the problem occurring in many research fields in which different agents and systems cannot make use of each other's results, due to employing different terms to describe the same underlying ideas (333).

Another relevant area within engineering system design would be the definition of specifications. When the design of a system is undertaken, the first step consists in the definition of requirements with which the final product must comply. Previous authors in the computer science field have stated (207; 333; 334) that the shared understanding and definition provided by ontologies can aid in the requirement identification process. This way, these specifications can be designated in a common and unambiguous way so that all involved stakeholders can share a common definition, which also prevents requirements to be interpreted in different ways. Within the area of KBE in the broad field of engineering design, it has also been stated that KBE approaches can be of aid in establishing an understanding between the customer requirements and the product's performance, which is fundamental to size it so that it complies with the required needs. One of the proposed approaches was to use ontologies for shared conceptualisation and definition of terms (230). In this case, this could be applied to aeroplanes, where precisely initial requirements are the first input of the whole design procedure. A correct labelling and identification of these requisites, as well as their interconnection with other concepts in the design process can constitute a great benefit. This is especially true for cases when the initial requirements can be of very varying characteristics.

Inference capabilities, enabled by the underlying logic of knowledge representation languages such as OWL, constitute one of the most significant added values of ontologies with respect to other systems that also serve communication and interfacing capabilities. For example, XML is employed by state-of-the-art data models for aircraft design environments such as CPACS (221) and ADML (240), which have already been commented in 4.4.1, and also within design environments themselves (232), for information interchange and establishing a common data format. XML is one of the possible syntaxes in which knowledge representation languages such as RDF and OWL can be expressed (207; 354). However, since XML does not have an underlying formal logic, reasoning cannot be employed in this format.

In contrast, OWL is built on formal semantics and therefore it supports reasoning capabilities, which include inferring new information from that which has been explicitly declared and also checking the consistency of the model. This consistency checking consists in inspecting the model to see if any data has been declared which does not conform to the schema defined at model level (an example schema and data can be seen

in Figure 5-8). For instance, if the user tries to add a property “wingspan” to a landing gear element, the system will check that the aforementioned category is not within those related to the concept “landing gear”. This allows for automatic model validity checking. This capability has been used by previous authors in the aircraft design field (345; 346), albeit it has not yet been exploited within the area of computational design environments. In this case, consistency could be checked with respect to the stages of the design process and the inputs and outputs of each one, as well as for limit values. For example, if the user intends to use a performance module intended for turbofan-equipped aircraft and tries to connect the inputs with the results of a turboprop engine, the system can detect that the elements conceptually do not match. As another example, if a structure is defined which surpasses the MTOW, the system can keep track of this restriction and warn the user of the inconsistency.

Finally, as mentioned in subsection 5.3.4, ontologies also allow for querying through the SPARQL format. This allows, for instance, to solve queries such as “which are the parameters influencing the wing sizing?”, to which the query will respond with all concepts that are linked through a certain property with the wing sizing process. Querying is also available in other paradigms such as Relational Databases (RDBs), but by using ontologies developers can take advantage of their explicit semantics and inference power.

The main communication and interfacing paradigms which are currently being deployed in aeroplane computational design environments are XML (for data representation and as a common language for aircraft definition) and UML (to define the interrelationships in a system). Note that XML is a data format without explicit semantics and reasoning power, while OWL represents an ontology implementation language which conveys logical consequences and explicit semantics based in description logic. OWL is not bound to XML, as many other serializations are possible, e.g. turtle, n-triples, etc., with XML being the first format in which OWL was available.

The main points which have been proposed here are summarised in the following list, where the added values of ontologies with respect to current methodologies is also emphasised:

- 1) **Providing a common formalisation of system and domain knowledge:** ontologies can serve to represent the system which is being designed (an aeroplane) or the domain itself (the design process) in a consensual and unambiguous way. Methods which are being employed in state-of-the-art aircraft design endeavours consist in UML diagrams (12), parametric models (232), XML (221) and knowledge repositories (95). The ontology paradigm allows to represent concepts and relations in a flexible and easily expandable way, in a way similar to UML, but in a machine-readable way and with the added benefits of the underlying logic allowing for reasoning capabilities. Knowledge mind-maps can also be represented through languages such as OWL. Furthermore, this knowledge representation language allows to represent not only hierarchical

properties of the type 'isSubclassOf', but also complex properties which can be user-defined such as 'hasSubcomponent', 'hasSource' or 'sameAs'. With respect to XML, once again the reasoning capabilities, explicit semantics and logic implications are the main added value of ontologies, aside from the fact that OWL is in a machine-readable format.

- 2) **Establishing a common model of the system:** whereas the previous point was centred to a larger degree in establishing a common knowledge model, here the focus is instead on system representation. This serves both to improve communication and engineering system design. Having a ontological model allows every stakeholder to work with the same assumptions, concepts and definitions. With respect to system representation, ontologies offer outstanding flexibility. In previous works, an ontology has been used to decompose an aircraft in subcomponents (199; 347; 346) in order to serve as a common reference in the conceptual design process. With ontologies, this decomposition could also be made with other criteria, such as by geometry or employing structural criteria. This application also falls in line with the trend in aircraft design of having a common geometric (232; 355) or data model (221; 240). As mentioned in the previous point, ontologies have the added value of their machine-readable format and the logic and inference capabilities achievable through their underlying semantics.
- 3) **Allowing to solve conceptual overlaps:** if two terms represent the same concept, even across different domains, with ontologies they can be established as synonyms through properties such as 'equivalentClass', therefore their properties become linked. This expressivity is not available in other knowledge representation paradigms employed in the state-of-the-art, or at least not with standardised and explicit semantics as is the case of OWL.
- 4) **Enabling explicit representation of assumptions:** made during the design process. Currently the format which allows to store not only product, but process information in aircraft design environments is CPACS. In the case of ontologies, the added value of representing assumptions within them is the underlying logic. Through this feature, it is possible, for instance, to check the consistency of the semantics representing these assumptions. For instance, a performance model which has been developed under the assumption of a three-term drag polar could check the consistency of the inputs to see whether a different type of polar model is being introduced, so as to give a warning or stop the design process.
- 5) **Allowing to store information provenance:** when compared with the strings used in XML to represent the source from which the information has been gathered as a comparison with the strings that represent it through XML, there are provenance ontologies that can semantically annotate this information rather than using plain text. This enables the advantages of automatic reasoning mentioned beforehand applied to this feature.

- 6) **Establishing networks of relationships:** since the different concepts represented in the ontology are linked through properties, the user can easily check which concepts are related with a particular one. This allows to deduce the which areas of the system will be affected before a change in any of the represented entities. The most similar current knowledge representation paradigm would be UML; however, ontologies incorporate advantages from Semantic Web Technologies. In addition, in the OWL ontologies, concepts from other ontologies can be directly reused, or even full ontologies can be imported, generating a global interconnected network. Moreover, publishing ontologies following best practices for ontology publication (356) allows the retrieve of information through the Web rather than working with local copies.
- 7) **Providing a common language to foster interoperability:** enabling machine-readable understanding and allowing to connect both internal elements amongst them and with external software. This is done through translators which convert information from the native language and format of each tool to the common reference ontology. Similar methods have been provided in state-of-the-art solutions such as CPACS (221) and ADML (240). However, being coded in XML, the reasoning and inference capabilities of ontologies would not be available with the former paradigm.
- 8) **Improving reusability:** by defining the concepts needed as inputs and outputs of each step of the process, these can be treated as “building blocks” and modified with other methodologies without affecting the rest of the system.
- 9) **Advancing specification definition:** through the common understanding that ontologies provide, the requirements of the system can be expressed in an unambiguous way, and they can be linked to the concepts within the system over which they will influence. Once again, with respect to current methodologies for specification definition such as UML, ontologies have the advantages of their explicit semantics, reasoning and being able to define restrictions, amongst others.
- 10) **Permitting reasoning capabilities:** allowing for consistency checking, model validation and inference of new knowledge. All of these features are provided by the underlying logic implemented in ontologies and based in the relations between the represented concepts. Cardinality constraints can also be established (for example, a commercial transport aeroplane must have at least two engines). These capacities are not within the ones of current state-of-the-art alternatives due to their lack of formal logic representation.
- 11) **Enabling query functionalities:** data queries could be enriched with inference power and, when publishing data on the Web in RDF annotated with OWL ontologies, federated queries could be executed over the Web towards more than one endpoint or knowledge base.

(a.2) Ontologies as a common model and language

As mentioned in previous sections, the disparity of methodologies, languages and tools constitute a hindrance towards effective communication among people, organizations and computers (333). Furthermore, this generates interoperability issues and reduces the possibility of reusing and sharing computational assets (333). A common paradigm both to represent models and to serve as a common language for all stakeholders is expected to ease these difficulties. Previous authors in the aeronautical engineering field also highlight that this heterogeneity is present in the aircraft design area (221; 238; 345; 346). Therefore, another proposed application of ontologies is proposed, this time more focused on their application as a common model and language geared towards software interoperability, collaborative design, multi-fidelity analyses and the design of unconventional aircraft

One of the drawbacks of the modular software architecture, which is mainstream in aircraft design environments, consists in the difficulties for seamlessly connecting the different modules and tools. This scenario is increasingly complex due to the addition of new modules to account for more disciplines during the design process, as mentioned in section 4.4. This in turn creates more interfaces amongst elements. Furthermore, optimisation process is also becoming more holistic, due to the larger number of modules which must be interconnected and correctly integrated into the process workflow (246). This integration is also more difficult when considering unconventional design, as previous authors have commented in their augmented coupling between disciplines (91). This all generates more potential issues in interfaces, increasing the need to establish common conceptualisations to avoid mismatches.

Previous solutions include common data formats such as CPACS (221) and ADML (240). As it was mentioned in the previous sub-section, these paradigms aid interoperability by establishing a common central node for communication amongst the different tools. This way, the aforementioned proposals can serve as a common model for all modules. Moreover, the number of interfaces is greatly reduced due to the software architecture having a central common node. These are the two main proposals currently in the state-of-the-art.

The possible added value that ontologies can constitute when compared with these paradigms was already mentioned previously, mainly: their underlying logic which allows reasoning capabilities, and a machine-readable format. The proposal would be to employ the ontology representing the system, which is being defined as the common central model, which can be defined geometrically, since it is the most common input for the discipline analyses. Moreover, within the ontology, as mentioned earlier, information about provenance and assumptions can be included semantically. Therefore, the ontology also allows to represent this kind of metadata compatible with the CPACS representation. Interfaces only need to be established between the ontology and each independent module, as in the case of CPACS and ADML. Furthermore, since the outputs and inputs of

each module can be directly linked with the concepts which they represent in the ontology, it also acts like a central node which needs just a translator to change the format from that of each module to the ontology schema and vice-versa. This is also similar to the capabilities presented by current data interchange formats. An additional capability of the ontology, serving as a common language, would be to connect with external software. The outputs of the tool can be linked with the concepts which they represent in the system allowing for a simpler translation between the external software and the proprietary design package.

The machine-readable characteristic, along with the semantic reasoning, allows to increase interoperability. For instance, the ontology can be queried to show all parameters related to a certain discipline, such as aerodynamics. Some of these parameters might also be simultaneously considered in other areas, such as the Aspect Ratio both in the aerodynamic and structural modules. The expressivity of the ontology allows to categorise this variable in the two areas, so that a query regarding the structural variables shall also output this parameter. This can aid to organize the order of execution of the analyses, depending on the available inputs to the design process, which is also linked with the requirements specification mentioned in the previous sub-section. Furthermore, the underlying logic can allow to check the validity of the connections. For instance, it can detect if the correct geometric data is being supplied to an analysis module, since it has the corresponding underlying concepts implemented.

This enhanced capability of connecting with external software also benefits multi-fidelity analyses. As mentioned in section 4.4, current aeroplane design environments usually draw upon external software to perform complex, high-fidelity calculations, such as FEM or CFD (55; 100). In this way, the design package usually implements methods of lower and medium-fidelity and then connects to specialized software for accurate calculations later in the design process. The interoperability previously expounded on that ontologies can provide is also extensible to the connection with external software. The ontology by itself does not augment the multi-fidelity capabilities of the design package, but it does allow it to connect more easily and reliably to the employed software. This way, ontologies constitute a robust and flexible paradigm to establish interfaces with this external high-fidelity software.

Taking into account this capability and attending to the fact that these higher fidelity analyses are increasingly required when analysing unconventional aircraft such as the non-conventional configurations explained in subsection 4.4.6 and RPAS, commented in subsection 4.4.7, the ontology also aids in these two aspects. Once again, the purpose of the ontology as a common model and language in these areas is not to increment the accuracy of the calculations, but rather to provide a seamless connection with the software that will be employed with this goal.

In the area of distributed and collaborative environments, ontologies are expected to constitute a noteworthy addition to improving communication. As mentioned earlier in

this subsection, the complexity level of modern aircraft require a through and very specialized analysis (218), which is often performed in distributed groups of specialists (96). This also calls for well-structured architectures to manage the interdependencies amongst the human and software components of the system. Previous authors in the computer science field have stated that a common understanding established on the base of an ontology can function as a unifying framework (333), since all stakeholders would have the same common model. This makes task-planning easier since, as mentioned earlier, all variables related to the field of aerodynamics can be obtained through a query, and their dependencies with other disciplines can be checked. The same process can be followed with a geometric decomposition. This has the potential to provide a powerful tool to improve planning between the different members in the consortium. In such a way, ontologies do not substitute workflow planning software tools and remote tool integration networks, rather they complement them. Another option is to search for all variables which are the responsibility of a certain stakeholder. As it can be seen, the formal logic underpinning the ontology is key to perform such queries.

Furthermore, and also referring to distributed and collaborative environments, but this time on the side of interoperability, these type of design contexts require an even higher focus on machine-machine communication. The different stakeholders will have various tools in order to perform diverse analyses. Acting as a common language, once again, the ontology can aid ease the interfacing issues, allowing all tools to connect with it as a central node, independently of the organization they belong to. Previous authors in the computer science field have also highlighted that manual conversion of formats is time consuming and error-prone (333). By adding a translator, data from different formats can be converted to the ontology schema. Even if one of the software tools from certain member of the consortium changes, it is just the translator that has to be changed, instead of the entire model. This automation of interfaces also aids in assuring the fidelity of the model.

As a summary, the main points which have been commented in this section, along with their comparison to currently used methodologies, follow:

- 1) **Establishing the ontology as the common, central node:** in a way similar to paradigms such as CPACS (238) or geometric-centered ones (232), but with the added value of their semantics which allow for consistency checking in the connections with each internal or external tool. The current formats provide a well-founded syntactic interoperability, which previous authors have recognized as showing opportunities for a future path towards including semantic interoperability (72).
- 2) **Setting links between concepts from the design package to external software:** therefore, serving as a semantic translator between the formats employed on both tools. If the external tool is compatible with the format of the ontology and available on the Web, federated queries encompassing both the

proprietary ontology and the external tool can be executed. This also aids in interoperability among different members of the same consortium employing different tools

- 3) **Allowing for semantic interoperability:** which allows to check consistency between the inputs and outputs within an interface, having defined the concepts that they represent. This semantic capability would not be available with current common data formats.
- 4) **Permitting query searches over networked information:** such as, for instance, searching for all variables which are responsibility of a certain member of the consortium, therefore allowing to ease the workflow planning within collaborative environments, without substituting specific software for these planning tasks.
- 5) **Encapsulating the central model from changes in external software:** by adding a translator, if the external tool changes, then just the translator has to be modified, not the whole model schema.

(a.3) Ontologies to represent parametric models

As expounded on subsection 4.4.1, one of the main focuses of current aeroplane computational design environments is set on incorporating KBE methodologies. One of such possibilities was the of parametric models, which have embedded certain knowledge of the components to be defined. Therefore, they can be used both in communication and interfacing, and to import the parametric model in other software.

Ontological representation of parametric models has been done in previous works, also in the field of Computer-Aided-Design (CAD) (357). As it was mentioned in section 4.4, one of the main opportunities of KBE application in computerised design environments consists in the development of parametric models that represent the aircraft which is being designed, which would aid in communication, since all stakeholders have a explicit definition of, for instance, the wing parametrization which they must use, therefore establishing a single model, in which the inputs and outputs of the process can also be defined. Interoperability issues are also tackled, since the flexibility of ontologies allows to represent diverse variants of the wing parametric model.

Furthermore, with this common parametric model, interoperability is further improved, since it will allow to connect the different systems and tools more easily, having an explicit definition of the model to be employed. With respect to engineering system design, this also allows to establish a re-usable model due to the parametrization and its connection with the diverse software elements.

(a.4) Ontologies for knowledge and data management

As mentioned in subsection 4.4.1 too, one of the main trends within KBE in aircraft computerised design environments is establishing knowledge management systems. The

complexity of the design process and the fact that it is a very knowledge-intensive procedure, as recognized in previous works (59; 95), sets the need to make that knowledge available in a explicit way for different stakeholders. The schema of the ontology model (the model level seen in Figure 5-8) is already a knowledge representation of the system or process which is defined, allowing for knowledge to be communicated more easily and unambiguously. Previous authors in the broad area of aviation have also proposed knowledge management applications of ontologies (337).

Furthermore, this knowledge can be stored in databases in varying forms. For instance, these could be the aforementioned parametric models represented through ontologies. Then, with querying, the database can be searched in order to provide the right information at the right time to the user which needs it (234; 333; 353) in order to continue with the design process. An additional use case of ontologies in this area would be to connect different knowledge bases through their interoperability capabilities. Previous authors in the broad aircraft design field have implemented this kind of knowledge management and search procedures employing ontologies such as DocO, DesO and ModO (348).

(a.5) Ontologies as an extensible (graph) model

In subsection 4.4.4, the topic of extensibility was expounded as one of the main trends and challenges of current computerised design environments, which has in some cases led to the development of new software with more extensibility (91). This characteristic was defined as the property allowing to change an element of a system or add a new one without significant changes to the rest of the program. As advanced aircraft concepts require increasingly complex analyses and more modules, it is a necessity that design packages have the capability to grow to incorporate these added faculties.

Ontologies have been highlighted by previous authors to have the capability of adapting with the changes in a complex and dynamic environment (358). This is achieved through several means, such as developing modular ontologies, setting minimum ontological requirements and minimizing encoding bias (333). As it can be seen, the paradigm of ontologies allows for scalability and flexibility. The flexibility in establishing new concepts and linking them with previous ones is one of their foremost advantages. Furthermore, different classifications can be made of the same system, which solves one of the main current issues in that the engineers had to decide on a particular hierarchy, for instance, either geometrical or systemic (72), which in the end must arrive to the same group of fundamental elements.

One of the ways of representing ontologies are knowledge graphs, with the nodes representing concepts and the links between them the properties that join them together. Previous studies, albeit not on the area of ontologies, have investigated the use of graphs to represent the design process and information flow (97). In this case, the graph represented the interrelations amongst the different areas of design and also the

optimisation process which was to be carried out. This study also mentions the feasibility of expanding the graph, since it consists in adding new concepts and their relations with existing ones (97). However, this technique has yet to be applied with ontologies and in the aircraft computerised design environments area.

Another advantage of ontologies is that they can represent the digital thread of the design process step by step. A previous work highlighted the relevance of developing applications and knowledge representations which could be suited to represent design processes from conceptualisation to manufacturing (230). Since the data employed in earlier phase is much fewer in volume than that of later ones, the graph can start from the basic input data and become each time more populated by adding new instances as the design becomes more defined. This can also be applied to properties. For instance, in the first phases of the aircraft project, the drag polar is usually considered as non-trimmed (7) (8), whereas in later phases the lift of the horizontal tail and its vortex-induced drag area considered. At this stage, a property can be established between the drag coefficient and the aspect ratio of the tail, linking these two concepts. This also aids in multi-fidelity analyses, since the proper level of accuracy can be employed at the right time when data is available for specific calculations. By applying semantic reasoning to this digital thread, ontologies can also allow to assure consistency between the different design phases, permitting the design to advance to the next phase when certain logical conditions are met. In previous works in the area of SoS engineering, a common semantic representation, for instance through ontologies, were proposed as a potential way to connect the different domains of the SoS design process (338).

The added values of ontologies in this area can be summarised in the following points:

- 1) **Establishing an easily extendible and scalable model:** which allows to add new concepts and properties depending on the level of development of the design.
- 2) **Graph representation and querying:** allowing for visual representation of the relationships amongst variables and other concepts. An added benefit of ontologies when compared with non-ontological graph models is the possibility of querying the graph in order to locate certain variables or the relationships of one entity with others.
- 3) **Logical conditions to ensure design process consistency:** establishing logical rules in an ontology representing the design process, in order to validate the process when the proper conditions are met. This is an added value with respect to graph approaches which do not include an underlying logic.

(a.6) Modelling RPAS and unconventional configurations

The topics of unconventional configurations and RPAS design within computerised environments were expounded in subsections 4.4.6 and 4.4.7. It was stated that these aircraft require particular design procedures due to their deviations from conventional

aircraft (59; 85; 91). This does not only include the software components which can be used, but also the proper description of the system, which can sometimes offer some ambiguity due to the design being largely different to conventional ones. For instance, in tailless configurations the volume coefficients are not defined, and for a tandem wing aircraft the reference surface can be selected with respect to diverse criteria.

All of the assumptions made during the modelling of these configurations can be made explicit through an ontology. An automated logical procedure can also be established so that if the aeroplane has certain characteristics, it will be classified as a BWB, as a joined-wing, etc. In this way, a model of the system aids in both human-human communication, human-machine interchange and in the area of engineering system design, since the unconventional aircraft system can be represented in a common, consensual and unambiguous way. Metadata regarding the provenance of information or even the level of fidelity of calculations can be made clear. For example, an ontology would allow to define a BWB configuration by establishing that it does not have tail components, instead of manually setting the values of the tail surfaces to zero. Therefore, ontologies constitute a robust way to model these particular configurations, with the added value of being able to implement a semantic logic which allows to validate the analyses selected. This point will be further commented in the following paragraphs. Finally, due to the difficulty in parametrizing unconventional configurations, ontologies can also aid in this task by providing a flexible model to define a consensual parametrization selected by the design team.

(a.7) Analysis selection and adaptation

As it was mentioned before, unconventional configurations and RPAS usually require specific sizing and analysis methodologies due to their differences with conventional aircraft. The selection of these methodologies is usually made manually, even though they may be included in an automated workflow of tool execution, they have been selected previously and located within the sizing or optimisation process, albeit some references seek to automate this workflow configuration for MDO processes (246). This is also the case in multi-fidelity analyses, where the analysis method has to be predefined even though it may be executed in an automatic workflow.

Ontologies can aid in this process of analysis selection. By establishing the concepts which must be defined in the system in order to be able to conduct a certain analysis, the system can verify whether the aircraft, at that particular design stage, is ready to perform the intended calculations. This could aid in multi-fidelity procedures, since the system can automatically verify when the conditions are met to perform the analysis, with a prior definition of the inputs that the analysis software requires. This can also be used to validate the selection of methodology performed by the designer, once again employing the inference and reasoning capabilities of ontologies.

Furthermore, in the case of unconventional configurations and RPAS, design software which incorporate the capabilities to analyse these types of aircraft usually include alternative modules or tools to be employed when sizing or optimizing the aforementioned configurations. The process therefore consists, for instance, when analysing a BWB aircraft, in taking the usual workflow for a conventional aircraft and substituting the analysis module which are not applicable (for example, a weight correlations calculation for conventional aircraft), with the alternatives specifically designed for the configuration of study (in this example, a mass estimation module for BWB) (59). Ontologies can define the interface of communication of these components in an unambiguous way, establishing semantic connections between the different modules. This could allow to interchange one with the other without affecting the rest of the system, and as an added benefit, these analyses can be classified and validated with logical reasoning. For example, if the ontology has classified the instance of the design aircraft as a joined-wing, then when setting up the analysis modules, it will find incompatibilities with the modules that would not be applicable in this case, so then the designer can choose in a semi-automated way amongst the remaining ones. In this way, if the design model has a series of predefined characteristics, it can be classified in one or other configuration and the corresponding analysis modules can be assigned. It is important to highlight that the ontology does not substitute the analysis itself, but aids in its selection, preparation and interfacing.

(b) Challenges: barriers for the development and application of ontologies for design environments

Having expounded on the opportunities of application of ontologies in aeroplane computerised design environments, the following section is focused on the challenges with respect to their design and implementation. A list of the different challenges which have been identified follows:

- 1) **Lack of ontologies in the aircraft design area:** albeit there are many more applications of ontologies in the broad area of aviation, which have been analysed by previous authors (337), in the areas related to aircraft design the number of ontologies is lacking. This limits the options with respect to ontology reuse, which, as commented earlier, is an advantageous process, since it also allows to link several ontologies in the case that they are submitted to the Web following the Linked Data guidelines. In previous research, the lack of engineering design ontologies in aeronautics when compared to manufacturing in the same area has also been highlighted (349). Albeit more general ontologies can be reused, the number of ontological resources which have been found for aircraft design are just four, with none focusing specifically on computerised design environments or in RPAS design.
- 2) **Limited ontology reuse capability:** related to the previous point, if there are few ontologies the possibilities of reusing previous resources is much more restricted.

Keeping in mind that ontology reuse has been cited by previous authors in the computer science area as being very beneficial with regards to time, capabilities and interoperability, this constitutes a substantial challenge in the design of ontologies in this area.

- 3) **Establishing a development community and standardisation entities:** in a similar way to the working groups of the W3C, it would be beneficial if the aeronautical conceptual design community could band together in order to develop join ontologies with shared criteria. This is currently a relevant barrier, since previous authors have explained that it would seem that many organizations have developed their own computerised design environments by themselves (91), therefore constituting a scenario where each design package has followed its own development process with differing criteria.
- 4) **Developing applications which exploit the capabilities of the ontologies:** in this subsection, several possible applications in the field of aircraft design have been proposed. However, these applications have yet to be carried out. Furthermore, new fields of application have to be investigated in order to broaden the scope of ontology applications in this area.
- 5) **Combining the ontologies with the Web of Things (WoT) paradigm:** this challenge proposes to establish representations on the Web of the entities represented in an ontology. For instance, if an aircraft prototype has several sensors and extensive analyses are conducted on this model, a Web representation of the values measured by the sensors can be created. Web services and applications can be created such as, for example, to emit an alert when the model reaches the stall condition in the wind tunnel. Queries to the Web service can also be conducted.
- 6) **Achieving open source and Linked Open Data principles:** in order to increase the reusability of components and modules, it would be needed that these ontologies are published according to Linked Data principles. This would allow to connect these ontologies on the Web and allow for accessible reuse, as well as making federated queries over the whole ecosystem. This constitutes currently a significant barrier, since most of the design packages are proprietary and not publicly available.

5.4. Summary and conclusions

In view of the interest and rapid expansion of AI applications in aviation, this chapter has studied different aspects related to the intersection of AI with other central topics of the thesis, specifically RPAS airworthiness and design. It is considered that this chapter constitutes an essential addition to the research conducted along the doctoral studies, since the topic of AI is tightly related to RPA, aside from being one of the areas with most

interest in aircraft design in the recent times. The potential of AI applications and their safe deployment is one of the main current challenges of the field of RPA, and it is one of the most dynamic areas in terms of rulemaking in the present years. Therefore, the possibility of investigating potential connections among RPA design, airworthiness and AI constitutes a promising prospect with remarkable synergies among the three areas.

From the initial analysis developed in this chapter, a key aspect which has been identified is the relevance of introducing safety considerations when studying potential uses of AI within the aerospace domain. The emphasis on airworthiness aspects is not only relevant to this chapter, as it is also one of the central ideas that will be present in part III of the thesis when developing the novel design methodologies for RPA, as one of the central ideas shall be to integrate airworthiness and certification constraints in the design continuum. Thereby, the prioritisation of safety concerns shown in this chapter as a whole is also aligned with the main perspectives of this thesis. The aforementioned emphasis on safety implications permeates the two specific lines of research which have been developed here, which are related to AI safety regulations and their link with those of RPA, and the opportunities of AI in enhancing RPA design approaches.

The line of research about AI safety and regulations in the broader field of aviation was tackled in section 5.2. As seen from the assessment of the current framework and efforts in AI rulemaking, the field is currently in its nascent stages. One of the main points that was highlighted is the connection between regulatory efforts and research in the area of safe and explainable AI, both in the field of aviation as well as in other areas of industry. This synergy, which has been explicitly commented by regulators (297) (65), could potentially accelerate the development of finalised standards and guidance material for AI evaluation and certification, as well as the adoption of formalised methods in industry consensus standards. This has been one of the reasons for performing an overview of the research landscape on safe AI within this line of research.

One of the most relevant findings from this line of research are the commonalities in rulemaking challenges between the field of RPAS, as seen in chapter 3, and that of AI, as developed here. Both are still in process of the establishment and consolidation of their regulatory paradigms. In both cases, a marked proportionality perspective can be seen, as developed both here and as seen in section 3.2, with the regulatory demands growing in parallel to the risk of the application. In the case of AI, there is a complex intersection between the system where AI is employed, the operation itself, and the AI algorithm itself, each of which contributes to the overall risk. Another key aspect discussed in this line of research are the different innate safety characteristics of AI models, based on the theoretical background provided in subsection 5.1.1. For instance, transparency and explainability are more easily achieved in symbolic approaches rather than in subsymbolic ones. Due to the connection of these characteristics with those of safe AI, the choice of AI model can have a relevant impact on the result of the overall risk assessment for each application. This could potentially lead not only to distinct

requirements for the certification of AI systems based on different models, but also to the potential preference of AI algorithms which present more desirable innate characteristics, at least for applications with a high degree of criticality. Thereby, the features of AI models and their choice can be expected to have a substantial impact on certification demands for aviation applications.

A key research contribution of this line of research has been presented in subsection 5.2.4, examining the current scenario of RPA and AI regulations and the possible connections between them, taking into account the present rulemaking prospects. This scenarios presents many relevant intricacies, such as the potential coupling between RPA-specific aspects through the future EASA CS-UAS, which is transversal to the current CS codes, that would provide the requirements of the aircraft independent of its piloted on board or remotely status; with the future Part-AI, which is also a transversal regulation to other specific provisions to be integrated in domain-specific rules. Since both rulemaking processes are being developed in parallel, it can be expected that mutual influences and synergies can be developed. The future directions and possible connections as established by the Authorities are yet to be seen.

With respect to the second line of research, that of possible AI uses in aircraft and RPA design, this was developed in section 5.3. It was seen that the interest on AI uses in aeroplane design are remarkable, with different studies employing distinct models for a variety of purposes. The main trend was that symbolic approaches were more widely used for the first design stages, which are characterised by a low number of parameters to define the aircraft model, and also by strong disciplinary couplings between distinct areas; whereas the subsymbolic approaches were leveraged with greater effect in preliminary or detailed design stages, mainly through enhancing optimisation processes with genetic algorithms or subrogate models generated over higher fidelity simulations. A key point to be highlighted, linking with the first line of research of this chapter, is that a focus on safety and explainability of models used at the design stage has seldom been emphasised in previous AI-related aircraft design approaches. This is in spite of the tight interrelation between the design processes and the safety of the resulting aircraft, as evidenced by previous works (9; 11; 48; 49). Thereby, the specific AI-based approach that was investigated in section 5.3 was also selected accounting for safety-related considerations.

Ontologies were chosen as the knowledge representation paradigm to be studied in this chapter towards their use to enhance RPA design approaches, and in particular, computerised design environments. The foundations behind this choice were discussed in detail within subsection 5.3.3, and it was seen that they provide many interoperability and knowledge modelisation advantages, and furthermore they could be used in symbolic AI agents with enhanced capabilities due to their formal semantics. In line with the safety concerns mentioned beforehand, they also deliver remarkable transparency and explainability, both on their own, and also within the AI models in which they can be

integrated. Thereby, their choice has been based on both design and airworthiness aspects, in line with the topics of the thesis. Furthermore, the specific design topic of computerised design environments was chosen due to the interest in them in the current aircraft design domain, as seen in chapter 4, and since one of the main lines of improvement of these software packages, as commented beforehand in the thesis, is focused on the use of enhancements to their workflow and software structure (51). Furthermore, both in chapters 2 and 4 a remarkable gap was detected in relation to computerised environments specifically tailored for RPAS.

The study of the opportunities of integrating ontologies in aeroplane computerised environments, as seen in subsection 5.3.5, provided several original prospects and concepts towards their integration in these design packages. The findings prove that ontologies can remarkably aid in many of the current challenges and trends that are being tackled in the area of computerised environments as developed in chapter 4. Each of those challenges was related to the main areas of application of ontologies, and several uses were detected. One of the main findings resulting from the contributions of this research is that the advantages that ontologies can provide can even solve many of the current hurdles in the field of computerised design environments.

In view of the results from this second line of research, it has been seen that ontologies can constitute an invaluable asset to aircraft computerised design environments. However, it is also acknowledged that this is but one of the many AI-based approaches which can enhance design methods, as seen in the state-of-the-art overview of subsection 5.3.1. There are many more opportunities to be exploited by different AI models in combination with distinct design areas, but each would require a thorough analysis like the one conducted for the particular case of ontologies so as to detect and discuss their range of possibilities. It was seen that subsymbolic approaches could be better suited for further design stages, such as preliminary design, where the aircraft is already defined in more detail with a wider range of data, and the remarkable potential of subsymbolic approaches in combination with optimisation processes can be leveraged.

In the case of most subsymbolic approaches, including GenAI ones, it was seen that their need for large volumes of data on which to conduct their training processes is one of the major hurdles towards their use in design (287). As an additional conclusion to be extracted here, and which could serve as a line for future work, it is noted that the generation of annotated conceptual design cases through the use of ontologies, which was commented in subsection 5.3.5 as one of their possible applications, could be of significant aid towards tackling the aforementioned hurdle. These cases, which would have been produced through the use of conceptual design methods, could be used, for instance, to train subrogate or GenAI models with convincing data. Furthermore, the fact that these design cases are annotated could open the path towards leveraging the underlying information and semantics embedded in their representation through neurosymbolic models, which could even aid in extracting more robust patterns from data through

subsymbolic approaches, and even GenAI models trained with the above-mentioned cases could yield results which are more feasible and practicable. In addition, it was seen in subsection 5.3.5 that ontologies are compatible with Semantic Web technologies. If the aforementioned design cases area made available in the Web through Linked and Open Data paradigms, their discoverability could be greatly enhanced, and this could also aid in mitigating the data availability bottleneck which has been identified for data-heavy subsymbolic approaches (320).

Undoubtedly, as mentioned beforehand, the field of AI in aviation presents many different dimensions, and its opportunities cover diverse areas, such as ATM, systems engineering, maintenance, safety data research, and aircraft simulations (64). Some of the insights developed within this chapter related to the influence of safety considerations when deciding the best AI technique with which to tackle the problem at hand could potentially be extensible to other areas, clearly after considering their particularities and the specific applications of AI that are considered in each case. It has been seen in section 5.2 that the interest in safe AI research also spans other domains not only of aviation, but of science and engineering in general. Thereby, it is expected that the intersection of safety and AI shall remain during the following years a subject with remarkable interest and impact.

All in all, the research on AI in relation to RPA design and airworthiness conducted here has provided several original insights on the remarkable opportunities and challenges of this branch of computer science in its application to these areas. As both the areas of RPA and AI are evolving rapidly, it is important that these findings are updated with future developments, such as the potential of hybrid AI models, so that their potential can be leveraged in the intersection between two areas with a dynamic and promising evolution.

6. OVERVIEW OF RPA CONCEPTUAL DESIGN METHODOLOGIES DEVELOPED IN THIS THESIS

The work conducted within part II of the thesis has tackled various of the key objectives of this research as laid out in section 1.4, covering both OBJ.1 and OBJ.2 along with its various specific goals. A thorough review of the current state-of-the-art of the field of RPA design has been conducted, as well as of several topics which are tightly interlinked with this area and that have shown particular developments in recent times. These have included RPAS regulations, aeroplane computerised design environments, and AI approaches for aircraft design. Part II of the thesis does not only include up-to-date surveys on the aforementioned topics, as original insights have also been provided on different aspects of these areas. These have included, among others, the main challenges regarding RPAS regulation coverage and specificity and how they can impact the aircraft designer, the main characteristics towards the development of computerised design environments focused on RPAS, and the remarkable advantages that ontologies can be provided when integrated within these packages. These insights are among the main contributions of the research documented here, as the perspectives provided were not found in previous works within these fields, and have sought to cover research gaps that were detected within those areas.

Aside from the contributions that part II has provided in itself, which are of the RCT.1 and RCT.2 types, it also serves a fundamental purpose towards tackling part III of this thesis, which is providing the state-of-the-art analysis and context to be taken into account when addressing the objectives of the thesis to be covered within part III. The foremost purpose of this part is the development of novel initial sizing methodologies for their use in RPA conceptual design applications, which therefore seeks to tackle the foremost objective of the overall thesis, as commented in section 1.3.

This brief chapter serves to present the global approach to the research and development of the novel design methodologies to be proposed in part III, as well as to lay out the foundations of the following ones, each of which shall focus on specific design approaches. Section 6.1 provides the main motivation driving the development of the design methodologies to be tackled in this part, being heavily based on the findings of part II. In view of these motivations, section 6.2 proposes the approach to be followed when developing the design methodologies that are the main focus of part III. It also expounds their distribution along their following chapters, as well as their combined form as an overall design methodology.

6.1. Motivation for the development of novel RPA conceptual design methodologies

The motivation and decisions for the development of design methodologies shall be based on the findings related to the state-of-the-art of RPAS design as seen during part II. This is so that the design methods to be proposed in this thesis answer both to relevant current gaps, as well as to promising development trends as seen currently in the context of the field. There are many points to cover from different areas of the previous analyses, which are presented and discussed here, and the aspects to be commented are heavily interlinked. Thereby, after the textual development has been expounded, a conceptual map shall be provided in the form of a figure later on.

The first subsection compiles some of the main points developed in part II regarding current areas of possible improvement in the state-of-the-art of conceptual RPA design, and introduces some of the dependencies that arise among them. The second subsection groups the aforesaid gaps in three main groups and discusses in more detail the links among them, also expounding on the influences that certain gaps have in the opportunities of covering other ones which are dependent on the first. This unveils an intricate set of interdependencies among the current challenges in RPA conceptual design. Finally, the third subsection highlights how this thesis has tackled some of the aforementioned gaps, and proposes how others shall be undertaken in the remainder of this third part of the thesis.

6.1.1. Compilation of current gaps in RPA conceptual design

With the purpose of developing novel design methodologies for RPAS, it is firstly important to detect the current research gaps in the field. A first set of aspects, observed in chapter 2, allow to pinpoint areas where presently there could be room for improvement. Below is a summary of aspects observed during the previous developments which have been crucial towards directing the efforts of this part of the thesis:

- As seen in chapter 2, initial sizing methodologies for RPA are very scarce in the open literature. From the categories of design works proposed in section 2.2, initial sizing methods were defined as those which allow to reach, from a set of initial specifications, an initial geometric definition of the aircraft. They are usually composed of smaller design steps, based on different types of procedures (performance, constraint analysis, statistics, etc.), so as to allow to reach the output mentioned above. In particular, only five references that propose approaches encompassing all of the steps required to reach this initial RPA definition have been found. This is in contrast with the domain of manned aircraft, where these methodologies are much more widespread.

- As mentioned in the previous point, overall initial sizing approaches are usually achieved by a combination of smaller design steps. In Figure 2-4, it was seen that initial sizing approaches are usually formed by the combination of other methods that are also within distinct categories as defined in section 2.2: statistical estimations, integral performance-based design, and constraint analysis. For these categories, as seen in Table 2-2, many more works can be found within the state-of-the-art. However, save for the statistical group, the rest of the cases are mostly AADM, with few GDM approaches. As commented in section 2.1.3 when defining these concepts, AADM tend not to be immediately applicable to a wide range of cases, as they have been developed to tackle a particular design case, whereas GDM are developed with the idea of constituting generic approaches that can be applied to a wide range of design scenarios. Therefore, in the fields of integral performance-based design and of constraint analysis generic design methods, there would also be potential room for proposing more design approaches for RPA of the GDM type.
- The field of statistical approaches has a remarkable number of previous works, both on the side of GDM as well as in that of AADM. However, as anticipated in section 2.2, the empirical relationships developed in them seldom cover some variables such as the tail volume coefficients or the fuselage length, which on the other hand would be key to conduct a complete initial sizing of the RPA, so as to be able to achieve the output required of the first phase of conceptual design. Therefore, there would also be room for improvement in terms of the number of variables covered by empirical relationship given within statistical approaches. This aspect will be covered in more detail within chapter 7.
- On the side of airworthiness-design, and mainly due to the nascent stage of the field of RPA regulations as covered in chapter 3, there are still very few approaches, both in terms of GDM and AADM, which integrate airworthiness requirements within the RPA design continuum. Considering the evolution of the regulatory paradigm and the current standards already in place, it would be remarkably desirable that the designer can include these aspects so as to ensure reaching a resulting design that is airworthy and certifiable.
- Regarding computerised design environments, there have been some efforts which have covered RPA as a possibility of air vehicle to be developed within design packages. This point will be developed in more detail further below in combination with the findings of chapter 4.
- Albeit the possibility of directly employing manned aircraft design methodologies to cover these gaps in RPAS design could be formulated, it would be preferable to develop new methodologies specifically tailored for RPA, or at least to adapt existing ones. This perspective, which seeks to ensure the adequacy of the design

methodologies employed for RPAS development, has been discussed and backed up in section 2.3.

In chapter 4, a more thorough analysis of the present situation of computerised design environments was developed. The main conclusions applicable to the work to be developed in this part III would be:

- In the broad field of computerised design environments, there are various challenging areas which constitute key hurdles towards the development of more effective and efficient design packages. Some of them are already being addressed by certain advancements in the field, such as the CPACS (237; 238) and ADML (240) data formats seeking to improve interoperability aspects. However, other challenges remain to be tackled to a greater effect. In particular, computerised environments compatible with the design of unconventional configurations and of RPA – which usually present unconventional layouts themselves – constitute a relevant area of improvement. Albeit there has been work done in higher fidelity approaches, initial sizing of unconventional configurations and RPA is seldom covered by these packages, as seen in one of the main conclusions of section 4.5.
- Moving on to the specific area of RPA computerised environments, and connecting with the bullet point of the previous list on this matter, both in chapter 4 as well as in Table 2-2, some packages covering the design of RPA were covered. The work of (61) corresponds to RAMP, a design environment specifically developed for preliminary design and optimisation of RPA. The research conducted in (64) is also a design tool devised in particular for RPA, and also focused on optimisation. The works of (114; 135; 136) are all focused on the particular RPA functionalities cover the same design environment, ADEBO, which albeit not developed specifically for RPAS, includes the functionality to design these aircraft, as demonstrated in the cited references. It is noted that ADEBO is also geared towards preliminary design and optimisation. Then, reference (93) corresponds to SUAVE, extensively commented along chapter 4, which has not been particularly developed for RPA, but it does have the option to model this type of aircraft. Once again, it is focused on preliminary design and higher fidelity methods. Finally, reference (70) develops the only computerised environment that has been tailored for RPA and which is focused on the conceptual design stage. In view of the above, and as commented elsewhere in the thesis, there is also a remarkable gap for conceptual design packages for RPA.
- It could be argued that other aeroplane design environments which include higher fidelity tools, which are more widely applicable to a variety of cases since they are based on physical phenomena instead of partly on semi-empirical approaches, could be used for modelling of unconventional configurations and RPA. However, this would be true for the preliminary and detailed design stages, but the gap in RPA design packages including initial sizing approaches remains.

- On another note, most of the design environments covered in chapter 4, as mentioned there, are of required payment, and the large majority are not open source or allow the user to check or modify the code. Therefore, the possibilities of reusing and tailoring them to other cases are severely limited.
- In view of the above points, aside from there being a gap on standalone initial sizing approaches for RPA as covered in chapter 2, there would also be room for improvement for computerised environments tailored for RPA that cover the initial sizing stage. Section 4.5 included several points which would be relevant towards the development of such design packages.

Finally, regarding the connections with the topic of AI design approaches, the following points summarise and further develop the main conclusions from section 5.3 which are applicable here:

- So far, there are few methods for design of aircraft, and less so for RPA, based on AI approaches. However, there is remarkable interest and potential for the field and the advantages that AI can provide to aircraft design.
- The majority of subsymbolic approaches are geared towards preliminary design and advanced stages within the design continuum, whereas symbolic approaches are more typically found in conceptual design and the earlier stages. However, as seen in subsection 5.3.1, there are also cases which do not follow this overall trend.
- Focusing on the conceptual design side, which is the main area of work of this thesis, no applied symbolic AI works for RPA were found in the open literature. The only AI-based methods used for RPA that were discovered for this phase are those of (45) and (47), which use neural networks, among other models, to derive empirical relationships from a database of RPA. Therefore, it is also clear that there is room for development in the area of AI methods for these aircraft.

6.1.2. Gap summary and interdependency analysis

Considering all of the above points, which have been gathered from the full analyses in part II, it can be seen that, in the domain of conceptual design of RPA, which is the main scope of this thesis, the following gaps have been found:

- 1) Generic procedures geared towards the initial sizing of RPA, including:
 - a. Statistical approaches covering a greater number of variables required for the geometric definition of the RPA.
 - b. Constraint analysis and integral performance-based design generic approaches (GDM) tailored for RPA.

- c. Overall encompassing initial sizing methods that start from initial requirements and reach an initial geometric definition of the RPA which can be used as a starting point for further designs stages.
 - d. The integration of airworthiness consideration in the above possible approaches, as applicable.
- 2) Computerised design environments specifically tailored for the conceptual design of RPA, which should include initial sizing methodologies, thus linking to the above.
- 3) AI-based conceptual design methodologies for RPA, particularly those using symbolic approaches, which would also enhance their transparency and explainability, being remarkably beneficial aspects to ensure the airworthiness of the design concept that is reached. However, it should be highlighted that, since symbolic models are based on formal rules, it would be beneficial to have a baseline initial sizing process defined beforehand, which can be used to create the rules or knowledge models. Thus, this links back with the first point covering the current lack of initial sizing methods themselves.

As it can be seen, there are tight interdependencies among the aforementioned gaps. These shall be analysed at three levels of granularity, from the more general ones at a coarser level, to those that are more specific.

(a) Gap analysis: coarse granularity level

Analysing the more general layer of the three main points listed above, to fully tackle the second and third main gaps, it would firstly be required to develop the new initial sizing methodologies as commented in the first point. In order to implement a design process within a computerised environment, it is required to have first the physical or statistical models that are to be codified in the design software. For conceptual design methods based on AI, particularly those of the symbolic kind, a similar dependency issue arises. In fact, in the case of the AIDA computerised environment for manned transport aircraft (76; 244), this AI-based design package implements several formal rules based on previous conceptual design methods such as those of (7; 8; 16). Therefore, and since the first gap of standalone initial sizing approaches for RPA also presents significant room for improvement within the state-of-the-art, this constitutes a noteworthy hurdle towards tackling the second and third gaps that have been detected. This is not the case for manned aircraft, where complete initial sizing methods, such as those proposed in (7; 16; 48) are very mature and have been tested in previous works, thus computerised design environments such as AAA (98), Piano (88), or FLOPS (223) have in some cases implemented them into their workflows. However, as mentioned in various points beforehand, the direct use of manned aircraft design approaches for RPA would not be recommended. Thereby, the need to firstly develop initial sizing methods for RPA so as to

implement them in design packages for RPA or as rules for symbolic approaches for AI-enhanced conceptual design of RPA would remain.

Furthermore, there would be an additional coupling between the second and third points for certain uses of AI in RPA design enhancement. As it was expounded on chapter 2, there are two main ways towards improving design environments. One is based on the development of novel design methods to be implemented within them, and the other in the improvement of computational aspects such as interoperability (51). As discussed in section 5.3, AI-based approaches can be used towards both objectives. However, when using them for the second one, that of improving computational aspects, a higher interlink with the structure and coding of the design environment arises. In the case of the proposal of possible uses of ontologies for enhancing aeroplane and RPA design environments as developed in subsection 5.3.5, many of them are related to the second point. Therefore, in some cases, the use of AI to enhance RPA design approaches could not only need having the basis of the standalone initial sizing processes predefined, but also the concept and structure of the design environment too. Thus, in those cases where AI is sought to improve design packages, the third point would require the second to be developed beforehand. Since there is currently also a gap in RPA design environments, this constitutes an extra hurdle for the development of AI-based approaches for this specific area.

In view of the discussion above, a new reason can be detected which can explain the reason for the gaps seen in the second and third points being more significant than those of the first. The current lack of RPA initial sizing approaches leaves little room for their implementation in design packages tailored for the conceptual design of RPA. The fact that there are few computerised environments for RPA design also affects the area of AI-related methods, which is in turn also influenced by the lack of RPA initial sizing methods.

Thereby, it could be argued that the first order of work in order to enable further developments in all three areas would be to tackle the first of them, that is, the development of novel initial sizing methods for RPA. This could allow for these methods to be implemented in design packages, and for AI-based approaches to be employed both to enhance the standalone design approaches themselves, as well as to improve their implementation in computerised design environments. This also means that, until a more extensive base of initial sizing methods for RPA is developed, it can be expected that the other two potential lines of work might not evolve as fast, in spite of also being significant gaps within the state-of-the-art.

(b) Gap analysis: medium level of granularity

The above has covered the connections and dependencies among the three general gap areas, detecting the criticality of advancing the first one so as to allow a faster work on the others. However, the development of initial sizing approaches for RPA also depends on the lower-level components of these methods, which are usually constituted by various

steps that allow to reach an initial geometric definition of the aircraft starting from the initial specifications. These dependencies and the way in which initial sizing approaches are based on the combination of other methods were seen in Figure 2-4 and discussed within section 2.2. Thus, a second discussion is developed here at a lower level of granularity, covering the influence of the constituting elements of overall initial sizing approaches on them.

As seen in Figure 2-4, initial sizing methods themselves are usually based on statistical approaches, constraint analysis procedures and integral performance-based methods. This is also the case in manned aircraft design. For instance, Roskam (8) considers firstly a mission-based method to estimate initial weights based on integral performance requirements, and then links this with a constraint analysis to reach an initial sizing of the wing surface and the powerplant, all while using some correlations and typical values extracted from statistical analyses. Further steps covering the sizing of tail surfaces also heavily employ empirical trends. The same can be seen for the few initial sizing GDM approaches of RPA as listed in Table 2-2. For instance, in the case of Gundlach (6), an initial weight estimation based on typical mass fractions is proposed, and at a later point it is followed by a performance analysis.

In view of this, the gaps detected in the three types of methods usually employed within overall initial sizing procedures also affect the possibility of developing the latter. Albeit there are many GDM based on statistical approaches, as mentioned beforehand, and as it will be seen in detail within chapter 7, few of them provide empirical relationships that cover certain variables, such as those related to tail surfaces, or to tail booms, which on the other hand are essential to reach an initial geometric concept of the aircraft. Regarding constraint analysis procedures and integral performance-based design, there are many works on the AADM side, but fewer that are generic and can thus be applied to a variety of cases. The issue of integrating airworthiness requirements both in these more granular methods, or in the whole initial sizing process, also remains to be tackled.

Thereby, following a similar line of thought to the one used at the coarser level of granularity, a new reason for the current lack of overall initial sizing approaches can be found through the discussion above. Since these methods are usually formed through the combination of smaller steps, mainly represented by the other topical areas commented here and introduced back in section 2.2, if there are gaps within those building blocks, the possibility of creating broader-scope sizing methodologies covering different steps until reaching the initial geometric concept of the aircraft will also be hindered. Some references such as (6) and (10), which are at the same time handbook approaches, have covered in the same place both the steps and the overall design process. It is seen that there is a relatively low reuse of methods which have been developed by some authors for the more specific topics within overall initial sizing procedures tackled by different authors. This is most possibly due to concerns regarding the applicability of the methodologies when trying to integrate those that have not been made by the own

authors who are developing a more expansive sizing process. In any case, the number of GDM approaches for constraint analysis, integral performance methods and airworthiness-based design remains low. Therefore, it can be concluded that the general lack of GDM procedures is impacting the reduced number of currently available overall sizing methods, which is similar to what happened at the previous level of granularity.

(c) Gap analysis: fine level of granularity

Furthermore, a more detailed analysis can be conducted now focusing on each of the topical areas mentioned above, and how their low number in certain cases (for instance, GDM of constraint analysis) is impacted by other factors. This analysis will be more thoroughly performed along chapters 7, 8 and 9. However, a brief overview is given here.

In order to explain the low number of methods available for some of the more specific design approaches mentioned beforehand, it is essential to go back to the main challenges of the field of RPA design as seen in section 1.3. A common denominator can be seen for many of them, and it is based upon the differences that they present with respect to manned aircraft in many aspects: ranges of values of typical parameters, mission specifications, different regulations, etc. After all, if these dissimilarities were not present, the methods from manned aircraft design would be more directly applicable. However, one of the main reasons for the need to develop new design methodologies for RPA, and also for the direct reuse of manned aeroplane methods not being advised, is precisely due to their differences with conventional aircraft. These differences are particularised at the level of each type of design method, resulting in specific hurdles. Albeit these will be fully developed further along the thesis, a brief outline is provided here:

- Statistical approaches: the lack of available data on RPA variables which are more specific in nature, such as tail surface areas, or fuselage diameter, are seldom encountered, in contrast to the field of manned aviation where this data is more usually found. Empirical relationships and typical values of manned aircraft would seldom be applicable due the small overlap in the ranges of the relevant variables (such as *MTOM*) between both domains.
- Constraint analyses: albeit the equations representing the constraints are based on physical phenomena and thus could be directly applicable, they usually employ empirical constants obtained from fitting data. These, again, would not be applicable for RPA. Furthermore, some constraints are governed by airworthiness regulations, which are starkly different for RPAS.
- Integral performance-based methods: as commented in chapter 1, RPAS have a marked multi-role nature. Most methods available for manned aircraft perform an initial sizing based on a single mission. Furthermore, the flight profiles that RPAS can follow to perform their missions are very varied and can present noteworthy differences with respect to those of manned aircraft. The fact that

many RPAS present high camber aerodynamic profiles so as to achieve better integral performance also makes the use two-term drag polar model debateable, therefore classical equations for integral performance modelling might not be applicable.

(d) Gap analysis: overall summary and remarks

In view of the above analysis, it can be seen that, albeit there are many gaps in the field of RPA conceptual design at various levels of granularity, the fact that there are key areas to be tackled at the level of the building blocks that can conform the broader methodologies can be identified as a root the effect of which cascades onward to affecting all of the higher granularity design methods. This might explain the observation already anticipated in chapter 2, and that is that the composite methods are less in number than the more standalone ones.

Most of the aforementioned hurdles could be tackled through an approach of directly using directly or adapting manned aircraft methods, but as mentioned beforehand this comes with various uncertainties regarding applicability. Furthermore, airworthiness aspects are very different for RPAS. The recommendation of focusing on the development of new methods is in line with previous authors such as (6; 10; 15).

Clearly, there are many other areas within the domain of RPAS design which also constitute noteworthy avenues for future research. These include the development of higher fidelity methodologies and their more efficient use, subrogate modelling on CFD and FEM simulations to create faster models for optimisation procedures, the analysis of airworthiness requirements on detailed design aspects such as the design of unions between components, and many others. However, since the scope of this thesis is focused on the conceptual design stage, and in particular, on rapid methodologies for the initial stages, those would remain outside the scope of this research. It should be noted that some of these other approaches, such as CFD and FEM, are less affected by some of the hurdles mentioned beforehand, as they model the physical phenomena themselves without using semi-empirical corrections, and could therefore be more directly applicable to RPAS. This was commented in chapter 4 as one of the approaches towards developing higher-fidelity computerised design environments. However, these types or methodologies would not be applicable to rapid sizing approaches nor comply with the scenario marked by the conceptual design stage. Thus, albeit of extraordinary use for other approaches, they would not be feasible for use within the scope of this thesis.

6.1.3. Approach of the thesis towards addressing RPA conceptual design gaps

In view of the previous analysis, there are many gaps to tackle within the state-of-the-art of RPAS design. This is expected to set up a very dynamic field of research in the near future within this domain. Clearly, the number of gaps that are present at different levels of granularity constitute an ambitious scenario which is not feasible to tackle in full extent

within this thesis, even when focusing on conceptual design as done in the above analysis. However, since all of these areas are in the forefront of the state-of-the-art and current research interest for RPAS, it is also desired to offer a coverage of their main challenges and current status. In this way, even if full methodologies cannot be developed for some of them, at least the proposal of original insights towards the further study of these areas could constitute noteworthy research contributions, given the current nascent status of many of these areas of research.

Considering of this, two different approaches have been followed in this thesis to cover the different gaps detected in the field of RPA conceptual design:

- 1) **Review, assessment and original insights:** this approach has been followed for those lines of research for which there are higher dependencies with other gaps, but which still constitute extremely relevant prospects. A review of the current work related to the particular field of study is conducted, which is followed by a discussion assessing the challenges and gaps, as well as how they are currently being tackled. Furthermore, original insights on various aspects are provided, such as the influence of these lines of research on the overall field of RPA design, the opportunities of different techniques that could be employed in those areas, and promising lines of development.
- 2) **State-of-the-art gap analysis and development of novel design methodologies:** this approach has been followed for those areas which are more fundamental in nature, with lower interdependencies, and which constitute root elements towards the development of other ones. Here, not only are specific gaps and hurdles of the particular area covered, but novel conceptual design methodologies for RPA are proposed.

This combined approach allows to tackle the main objectives of the thesis, as laid out in section 1.4. As seen beforehand, it is currently a complex endeavour to develop from scratch a new computerised design environment for RPAS, particularly since there are very few methodologies that can be implemented, and furthermore some of them present various areas of improvement which were mentioned at the finer level of granularity in the previous subsection. However, due to their relevance, it is still sought to provide contributions within them. This is the approach that has been followed along part II of the thesis, where for each of the areas of RPAS regulations, computerised design environments and AI-based approaches, not only were thorough reviews conducted, but each chapter also contained some original insights on those subjects. These can be considered as one of the types of main contributions of this thesis.

In contrast, for the design approaches at a finer level of granularity, as there are no previous interdependencies, these can be tackled in a more detailed manner within the scope of the thesis. Thus, the second line of work is followed for the area of initial sizing methodologies for RPA, as well as its related topical areas which serve as building blocks

for the overall sizing process. These are the topics that are to be tackled in this part III, where the main contributions shall be a series of design methods covering the areas of statistics, airworthiness, and integral performance; and finally, a combined initial sizing approach that leverages them in a joint manner. This suite of conceptual design methods of RPA covers the second main objective of the thesis as laid out in section 1.4. Another reason for following this more detailed approach for these topics, is because they have been detected as being a contributing factor for the gaps present in the domains at a higher level of granularity such as computerised design environments. Thus, the development of new initial sizing methods is also expected to aid in accelerating those lines of research at a higher level, since more building blocks to develop and implement them will be available.

In spite of the methodologies to be developed in this part III being at a lower level of granularity than some of the aspects studied in part II, there is another fundamental reason for having delved in depth in the topics of the previous part, aside from the standalone that those analyses had on their own. This is, to use some of the perspectives gained from those topics such as computerised design environments, to keep them in mind while developing the design methods covered in the following chapters. Considering these aspects, the methodologies developed here can be better prepared for their inclusion within future AI-based approaches or computerised design environments. All of these threads shall come together in part IV.

The previous exposition has covered the different main gaps detected in the field of RPA conceptual design, their complex net of dependencies, as well as their relationship to the ways in which they are tackled in this thesis. A summary of this information can be found in the conceptual map illustrated in Figure 6-1.

6.2. Suite of RPA conceptual design methods: development approach and structure

In the previous section, it was seen that this part III of the thesis shall tackle the objective of developing new design methods for the initial stages of RPA, thus covering the second general objective of the thesis as laid out in section 1.4. The final purpose is to develop an initial sizing process which covers the full steps from the initial requirements statement up to the definition of a conceptual geometry of the aircraft, which can then be used as a starting point for further design stages. However, as it will be commented further below, it is also sought that each of the design methods has value on its own as a standalone process. This is expected to aid their modular integration within further design approaches that are more encompassing in nature, among other possible aspects. Thereby, both perspectives of the particular aspects of each design approach, as well as that of their possibility of forming an overall initial sizing process, shall be considered.

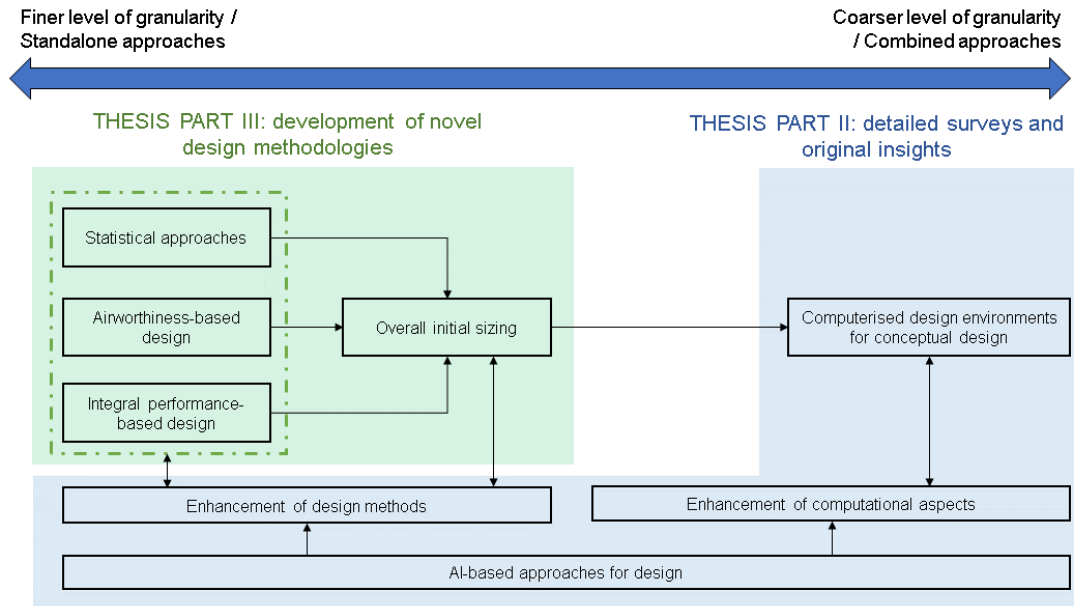


Figure 6-1. Conceptual schema of topical areas of RPA covered in the thesis, their relationships and the contributions of each part of the thesis related to the topics.

As a relevant point, the design methodologies to be developed within this part of the thesis shall be of the GDM type. This has been decided so as to enhance their applicability range to a wider variety of cases. As mentioned in the previous section, one of the main issues towards developing design approaches with a coarser level of granularity is the lack of generic methods at the finer level. Therefore, by developing the design methods so that they can be applied to a wide variety of cases, their reusability is enhanced, and thus their perspectives of aiding to tackle the issues at the level of initial sizing or computerised design environments are also improved.

In the following lines, the different design methods that will constitute the building blocks of the overall initial sizing approach shall be introduced. Albeit they are developed in full detail within each of their chapters, a brief mention to some of the current challenges which are sought to be undertaken is commented in the following lines.

As seen in classical manned aircraft design approaches such as those of (7; 8; 9; 11; 48), as well as in more recent RPA design procedures (6; 10), the overall initial sizing process usually comprises three or four of the topical areas described in section 2.2, and illustrated both in Figure 2-4 connecting to the initial sizing one. These are: statistical approaches, constraint analysis, integral-performance based design, and airworthiness-based design. In view of the good results that the use of these approaches has yielded, both separately, as well as in combined form, in previous works, these shall also be the focus of the design approaches to be developed here.

When seeking to combine the different design methods into an overall initial sizing approach, it should be noted that the ways in which these design approaches are

combined are largely dependent on each author. For instance, in the case of Roskam (8), as mentioned beforehand, the process starts with an integral performance approach, and flows on with a constraint analysis procedure, with statistical relationships being employed at different points through the process. Thereby, the overall conceptual design process need not be a consecutive connection of the different topical areas, rather, some can be integrated within others, as long as the final result is an initial geometric definition of the aircraft.

A brief exposition of each of the individual design methods to be developed within this part of the thesis is commented below. Here, not only are their characteristics as standalone methods emphasised, but also potential considerations regarding their combined use for the full conceptual design procedure:

- **Statistical approaches:** in spite of the widespread use of this type of method within RPA, even on the GDM side, it was commented beforehand that there would still be specific gaps to cover here. Most of the current empirical correlations available for RPA have only been obtained for general design variables such as the *MTOM*, wingspan, or wing surface. There is room for improvement in obtaining further ones dealing with variables that have a more specific nature, but which are also fundamental towards completing the sizing of the aircraft. These are, for instance, the surface areas of the tails, or the length of the tail booms. Thereby, the statistical approach to be developed here shall seek to consider further variables which can aid in completing the initial geometrical definition of the aircraft. Albeit the empirical correlations to be obtained here shall be integrated along the other design approaches developed in part III, the objective shall be to generate a standalone sizing approach based on the statistical relationships to be obtained. As a further highlight, two different approaches shall be developed: one based on the classical regression approach, and another one built upon the factor analysis methodology, which constitutes a novel approach within aircraft design. Chapter 7 shall deal with the development of these design approaches.
- **Airworthiness-based design:** in view of the remarkable developments within RPAS regulations in recent times, as seen in chapter 3, and the impact that they have on the development of safe and certifiable designs, it is considered that the investigation on design methods based on airworthiness regulations constitutes a noteworthy addition to this part of the thesis. However, there are significant challenges to overcome, such as the disparity among the requirements demanded by the different standards (as seen in section 3.5), and also the wide variety of categories of RPAS. Thereby, a different approach will be proposed here compared to the usual airworthiness-based design procedures found in the literature. Instead of developing a single design method based on a particular regulation, a flexible approach shall be developed, which aids the designer in extracting the applicable requirements from the standards, and also in integrating

them into design methodologies of generic scope. Its application shall be demonstrated in the development of a constraint analysis approach which will be populated with certification requirements. Chapter 8 will cover the development of the flexible airworthiness-based approach, as well as the application to a constraint analysis method.

- **Integral performance-based design:** as commented beforehand, RPAS have many different characteristics to their missions when compared with traditional manned aircraft, with one of the main differences being the marked multi-role nature of RPAS. Thereby, it can be seen that new mission-based approaches that consider to a greater extent the particularities of RPAS would provide a relevant addition to the landscape of conceptual design for these aircraft. The method to be developed here shall reconsider many of the hypotheses found in traditional approaches of this kind, some of which are the use of a two-term drag polar, the consideration of a fixed flight profile, and the assumption of constant propeller efficiency, among others. Chapter 9 covers all of these aspects, along with the development of the method itself.

As it has been seen, one of the main objectives is to make each design approach completely functional on its own, even if they can then be used in a combined manner within an overall initial sizing process. Once the development of the standalone procedures has been tackled in their respective chapters, the combination of them along with a case study shall be conducted in chapter 10.

As a final note before moving on to the development of each of the design approaches, some comments regarding the influences that the findings from part II have had in certain decisions taken along this part III are highlighted here:

- **Modularity of approaches:** as seen in chapter 4, the preferred structure for computerised design environments follows a modular approach. In preliminary approaches, these modules usually correspond to each of the disciplines involved in the optimisation process. However, in conceptual design packages, they can represent each of the different steps taken during the initial sizing. Thereby, if the design methods developed here are sought to be integrated in a computerised environment, an adequate criterion to consider shall be their modularity. This is one of the reasons for the above-mentioned objective of making each design approach standalone, but with the perspective of then being able to combine them into a combined design process. As another note, in this case related to ontologies, which were investigated in chapter 5, modularity would also be compatible with this knowledge representation paradigm. The development of ontologies usually emphasises their modularity and reusability (359). Thereby, if an ontology would be developed to describe the process in each design process, they could also then be combined to represent the full approach. Thus, the decision to make these

design approaches modular also connects with the potential design of ontologies to represent these processes.

- **Consideration of initial sizing process:** one of the main conclusions from chapter 4 was the need of new initial sizing methods for RPA, which were needed for the development of new computerised environments focused on these aircraft. The objective of developing an overall initial sizing approach here is therefore also linked with this purpose towards accelerating the development of design packages for RPA.
- **Consideration of reciprocating engine aircraft:** as also commented in the conclusions of chapter 4, a majority of RPA employ piston engines. Therefore, and in particular towards the development of the integral performance methods, this type of engine shall be taken into account. As it was mentioned in chapter 4, electric motors are also relatively widespread. However, as it will be seen in chapter 7 when compiling the database of RPA employed for extracting statistical trends, this category of RPA has a lower number of aircraft and presents a larger heterogeneity than that of piston engines, complicating the derivation of empirical relationships. Furthermore, this type of powerplant is mostly found in small RPA, which are the ones that have the least restrictive regulations, as seen in chapter 3. Thereby, the focus shall be placed on the aforementioned reciprocating engine ones. As an additional distinction, many RPA have fixed-pitch propeller. This has been fundamental towards one of the decisions made in the development of the integral performance methods, which is to consider variable propeller efficiency, as it will be further developed in chapter 9.

As it can be seen, the findings from part II, even if they have been focused in different (but tightly related) topics to those covered here, have also had a significant effect on the decisions made here for the development of the design methodologies.

7. STATISTICAL APPROACHES FOR RPA CONCEPTUAL DESIGN

This chapter covers the first of the three main lines of research on novel design methodologies for RPAS as outlined within chapter 6, which is that of statistical-based approaches. It was already seen in section 2.2 that the topical area of statistical studies for RPA design is among the most dynamic ones in this field. This kind of approaches fit within the rapid calculation procedures according to the requirements of the conceptual design stage. They also showcase a very high degree of reusability, which allows them to be integrated within other methods that have a broader scope, such as initial sizing procedures and even computerised design environments. Even in this latter area, as seen in chapter 4, the development of new rapid sizing methods for unconventional layouts and RPA was highlighted, which is firstly required so as to then implement these approaches in design packages (18; 70). This was one of the main reasons for proposing in subsection 4.6.2 of this thesis the development of novel rapid design approaches for RPA among the foremost future lines of work towards enhancing the development of design suites for these aircraft.

However, both within the review of chapter 2, and as also commented in chapter 6, it was brought forward in advance that, in spite of the comparative quantity of works in this area, there are still remarkable gaps that should be addressed. One of the areas of future work which was identified corresponded to the comparative lack of statistical approaches to size the tail surfaces, fuselage, and tail booms of RPA. Furthermore, considerations related to the distinct types of general arrangements have been mostly neglected in previous statistical studies. Improving these aspects would not only provide a broader scope to current methods, as they would also be key to further enhance overall initial sizing methodologies so that they can cover a larger array of design variables for RPA.

All of these considerations substantiate the interest in research objective OBJ.3.1 of this thesis, which is the one to be addressed within this chapter. A fundamental part of this line of research has been the compilation of a database of existing RPA designs. Two distinct statistical methodologies shall be employed: statistical regression and factor analysis, with this second type of approach constituting a novel prospect within this area. From the models obtained from the application of these approaches, two novel design approaches will be proposed, which would fall within thesis contributions of the type RCT.3. These design approaches do not only have use by themselves, as later on within chapter 9, they shall constitute one of the fundamental elements towards the development of the multi-role RPA sizing methodology to be developed there.

7.1. Chapter introduction, overview and structure

The area of aircraft conceptual design faces several changes in the process of performing an initial definition of the aeroplane which is being designed. Some of these issues were expounded in subsection 2.1.2, and they include the fact that at this point, there is few information available on the design concept of the aircraft, since the objective of the first steps of the design continuum is precisely to perform an initial estimation of the geometric and mass characteristics of the aircraft to be designed via the use of synthesis approaches. This first approximation to the design concept is then used as a starting point for its refinement in further stages, where a larger volume of data is known, thus enabling to use higher fidelity approaches. As it was seen in 2.1.2, in spite of the fact that scarce information is available in the conceptual stage, the criticality of the decisions made at this step is remarkable, and the choices made here have large impacts downstream the design process on later stages (11).

One of the foremost resources employed by aircraft designers in these first phases, where the aircraft concept has yet to be generated, is the use of statistical results and empirical relationships extracted from previous aircraft (39). These approaches constitute rapid-sizing procedures that need few input data, thus fulfilling two of the main features required of conceptual design methodologies. Furthermore, they show a paramount advantage in that these statistical results are obtained from previous aircraft which have already been tested and deployed. Thereby, even if typical values or empirical relationships are not directly used in sizing procedures, they are often leveraged to check the validity of the obtained aircraft concept and to compare it with previous viable designs (11; 39).

With all of this, and in spite of the computational advancements of the recent years, the value of statistical methodologies in aircraft design keeps being highlighted, and it continues to be an area of research receiving ongoing attention within the overall domain of aircraft design, as seen in the following references of the area of manned aircraft (42; 44; 104; 360). Furthermore, as mentioned beforehand in chapter 4, and in spite of the emphasis on high-fidelity approaches, rapid calculation methodologies for the conceptual design phases are also still highlighted in recent times. Thus, there is interest in the development of new rapid methods for the initial design space exploration and sizing of unconventional aircraft, including those with atypical layouts and also of RPA (18; 58; 60; 70; 259). The reusability of these statistical approaches, which can be integrated in many different design methods as discussed in chapter 2, further reinforces the interest in this area.

In spite of the usefulness of these approaches, their application in aircraft design sizing procedures should be done with caution. Firstly, the applicability range of statistical results should be considered when assessing whether they can be employed for a certain design case or not (16; 18; 50). For instance, correlations obtained for jet-engine aircraft might not be applicable to piston-powered ones, which could follow a different trend (7).

As another example, regressions for mass estimation of manned aircraft present significant differences depending on whether they are obtained for ultralights, normal category aircraft, transport category aeroplanes, or military vehicles (8). These are only some of the possible aspects which may cause significant variations in the underlying trends. The applicability is not only dependent on categorical aspects of the aircraft, but also in the value ranges of the data employed to estimate the regression. For instance, a regression for small manned aircraft, which could have a lower limit of MTOM around the range of approximately 800-1000 kg, would not be applicable to other vehicles which have lower values of MTOM, which could be the case of most RPA (16). Thereby, when studying an area of aircraft design where few previous correlations are available for the variables of interest, it is usually required to obtain new statistical models from databases that also have to be compiled towards this purpose (18; 39).

Furthermore, statistical results should also be carefully assessed regarding their significance and accuracy. The quantity and quality of the data with which the statistical results are obtained has a remarkable impact on the regressions that can be extracted as well as on their representativeness. This constitutes a relevant factor to account for when addressing the development of statistical approaches, and in some cases significant hurdles might arise from this, as the designer has no direct control on the data that can be found within the state-of-the-art. Finally, it is key to assess metrics such as the coefficient of determination and the standard error, as well as to conduct hypotheses testing procedures, so as to ensure the validity and inference capability of the obtained results.

Considering the above, the development of novel statistical approaches which are applicable for RPA is one of the foremost lines of works towards enhancing conceptual design methods for these aircraft. As brought forward in advance within the findings of the overall survey of section 2.2, and as it will be commented in more detail through this chapter, there are already research works within the field of RPA design that, in the latest years, have sought to extract novel empirical relationships from data of existing RPA models, so as to allow designers of these aircraft to benefit from the advantages of statistical results. As it was seen within Table 2-2, this is one of the topical areas with a larger number of GDM design approaches. The number of AADM works is also relevant, with these representing both the specific design cases where either previous statistical relationships obtained in GDM works have been leveraged, and also those investigations where specific values were obtained which were applicable within the boundaries of the particular design study of consideration.

In spite of this, previous research has highlighted the scarcity of statistical analyses on RPA designs (39). This is due to the diversity and thoroughness of the trends available for manned aircraft being much larger within the open literature, as it is a field which has been actively studied for a longer period of time. Furthermore, and as it was outlined in chapter 2, and as it will be developed with more detail in this chapter, in spite of the multiplicity of works, there are some gaps which difficult the use of these approaches in

overall sizing methodologies of RPA. One of the main issues comes from the fact that the diversity of design variables which have been studied in previous RPA statistical research works is comparatively low when compared to those analysed in manned aircraft ones. For example, the investigations in the field of manned aircraft of (42; 44; 104; 360) all extract trends and typical values pertaining to the tail surfaces, which are fundamental elements in the first stages of definition of the aircraft concept, in great part due to their influence both in aerodynamic aspects as well as in stability and control considerations of the whole vehicle. In contrast, among previous studies in the field of RPA, only two include regressions and typical values covering these elements of the aircraft (38; 116). Other relevant design variables which are fundamental in the definition of the initial concept of the RPA, but which are not readily available in previous works, would include the fuselage and tail boom dimensions. The fact that these variables are not available in rapid statistical procedures hinders their definition in the initial stages of design, which constitutes a significant disadvantage when compared to previous work in the manned aircraft design domain.

It should also be noted that the process of obtaining satisfactory statistical trends for RPA design so as to then use them within sizing procedures presents various challenges. Some of these are common to the field of manned aeroplane statistical approaches, whereas others constitute greater hurdles in the specific field of RPAS due to its particularities and differences. The applicability considerations mentioned beforehand are one of the main reasons for empirical results extracted for manned aircraft not being directly applicable to RPAS, requiring the development of new estimations (15; 18; 35). Furthermore, it has been noted that, since the surge of activity in RPAS design and development has occurred relatively recently, there is not a large volume of data available, resulting in designers having far less historical guidance to rely upon (35). This affects the quantity of data which can be gathered, which as mentioned beforehand, is one of the key aspects towards the quality of statistical results. This aspect is further complicated by the fact that, in the field of RPAS, there is a general difficulty to gather information on certain variables, such as the values of the wing and tail surfaces, even when consulting reputable sources of information, as their values are not made available neither by the manufacturers or by other resources. This hurdle has been remarked in previous research (15; 39; 61), and it will be analysed in more detail within this chapter. Finally, an additional difficulty results from the large diversity of design solutions in the field of RPAS, being higher than that of manned aviation and showing an abundance of layouts which would be considered unconventional therein (21; 35), as already discussed in chapter 1. These aspects might explain some of the hurdles and gaps found within previous studies on statistical approaches towards RPAS design.

In spite of the aforementioned challenges, there are promising advantages which can result from further advancements in the development of statistical approaches for RPA rapid sizing, which constitutes the area of research of the present chapter. The first step towards obtaining new design trends of fixed-wing RPA is the compilation of a database

that gathers information relevant to the scope of the conceptual design methodologies to be developed here. This constitutes a sizeable task, particularly taking into account the variety of layouts and characteristics seen in current RPA designs, along with the aforementioned issues related to the lack of available information. Once this database is compiled, statistical methodologies can be employed to extract trends representing current design practices used in existing designs. It should be highlighted that the results from this analysis do not only depend on the underlying data, but also on the statistical method applied to it. Firstly, an approach based on the estimation of statistical regressions shall be employed. This is a classic and proven process in the field of aircraft design which has yielded remarkable results in previous works. Furthermore, with the purpose of unveiling design trends that may not be captured by the aforementioned approach, it is also sought to apply a novel statistical method which follows a different perspective. This shall be the factor analysis process, which is a multivariate technique that allows to detect underlying trends within the observable variables through the extraction of a set of latent factors. Its mathematical basis and the prospective advantages that can result from its application to RPA design shall be expounded in detail later within this chapter.

The above-mentioned statistical methodologies allow to obtain various results that serve to modelise the design trends observed through the RPA included in the database. These results have significance on their own, as they describe the current design practices of existing RPA. However, the final objective of this chapter is to develop novel statistical sizing approaches for these aircraft. Therefore, two different design workflows will be developed in which the statistical results obtained beforehand shall be integrated, generating a systematic method to obtain various RPA design characteristics from a set of inputs. These procedures will then be tested through use cases to evaluate the accuracy of their results. The statistical approaches developed here can not only be employed by themselves, as these kinds of methods are highly reusable as seen beforehand, which will be seen within chapter 9 where they shall constitute an essential part of the multi-role initial sizing approach to be developed there.

The structure of the chapter follows the guidelines outlined in this introduction. Firstly, a more detailed analysis on the state-of-the-art of statistical approaches for RPA design will be developed in section 7.2. Then, common statistical concepts which serve as basis for both the regression and factor analysis methods are introduced in section 7.3. The following step consists in expounding the materials and methods to be used in this chapter, including the RPA database compiled as part of this thesis, and also the mathematical formulation and hypotheses employed in both statistical approaches. These aspects are crucial for evaluating the validity of the statistical results obtained in later sections, as well as for their adequate interpretation, and they shall be covered in section 7.4. Then, an outline will be provided of some of the challenges to be faced in the forthcoming RPA statistical analysis, which is done in section 7.5. With all of this, sections 7.6 and 7.7 respectively present the results from both statistical analysis approaches,

along with the design methods proposed based on each of them, leading to then conclude this chapter in section 7.8. This chapter workflow is illustrated in Figure 7-1, which also highlights the connection with further research lines of the thesis.

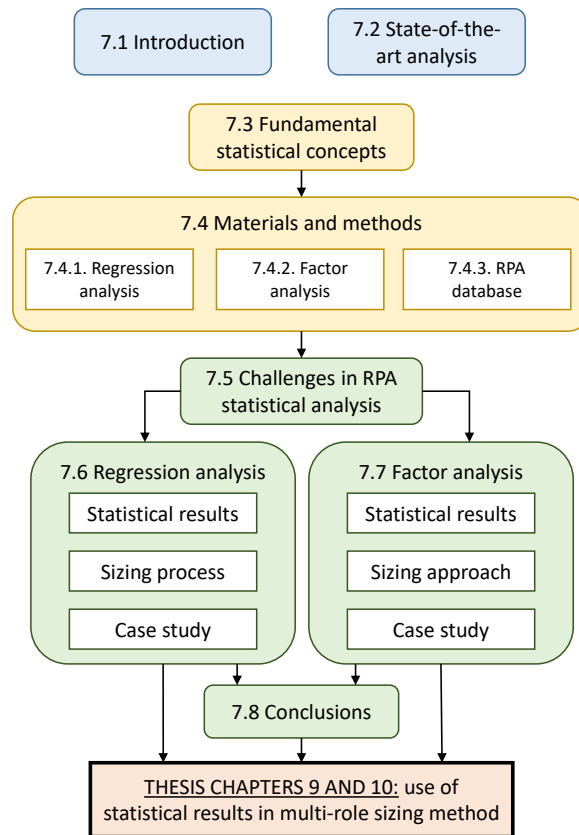


Figure 7-1. Workflow of chapter 7 and connection with other lines of research of the thesis.

7.2. State-of-the-art of statistical approaches in RPA design

As mentioned beforehand, manned aeroplane conceptual design has historically relied upon statistical methodologies for aircraft sizing, complemented with the knowledge and criteria of the different subjects that intertwine in the design and performance estimation of aircraft. Some of the steps which can be observed in these works include:

- 1) The compilation of a database of existing aircraft models.
- 2) A description of the overall characteristics of the aeroplane sample contained within it, usually illustrated through charts such as histograms and scatter plots.
- 3) The extraction of trends and interrelationships among distinct variables through the use of statistical approaches, with the use of regression analysis being the most common.
- 4) In certain cases, from the above-mentioned statistical results, a design workflow is proposed. This can be done by combining the different regressions estimated

from the database with other procedures, such as the use of typical values for certain variables. These workflows can then be combined with other design approaches to form a more holistic procedure for aircraft sizing.

Many of the classic methodologies of conceptual and preliminary design of manned aircraft which are contained in design manuals employ different combinations of the steps mentioned above. Furthermore, as mentioned beforehand, in recent years there is an interest on further improving current sizing methods for manned aeroplanes and in developing new ones, usually focused on novel or distinct design concepts. Therefore, classic approaches have been expanded by diverse authors for various manned aircraft configurations, yielding new results and methodologies (42; 44; 104; 360). The use of different aircraft classifications to adequately group the aeroplanes contained in the sample and obtain meaningful results is one of the key points of these works.

In some cases, new statistical results are obtained for a particular aircraft type and are then used alongside other design approaches. This is the case of the works of (361; 362), where new statistical regressions are obtained for purely electric and hybrid aeroplanes, which are then employed alongside matching diagram and optimisation procedures. This includes the use of typical values for aircraft similar to the one which is going to be designed, which often have to specifically derived for certain particular missions, such as in the work of (83), where the statistical analyses would fall within the AADM approaches considered in this thesis. Aside from regression analysis, other statistical procedures for conceptual design have also been investigated, such as analysis of experiments and response surface methodology in order to scan the design phase for optimum solutions (363), or in the development of simple models describing specific physical phenomena for rapid calculations to aid in the initial design phases (364). Overall, it can be seen that the derivation of conceptual design methodologies from statistical procedures applied to a sufficiently extensive and robust database constitutes a proven technique for manned aircraft design.

Moving on to the domain of statistical methodologies for RPA, as outlined in section 2.2, this is one of the conceptual design areas for these aircraft which has seen a larger development of work in the recent times. Some overall trends and gaps in these works have already been outlined beforehand in the thesis. These are complemented here with a more detailed overview of some of the works currently found in the open literature. Table 7-1 provides a summary on noteworthy recent contributions in the field of RPAS statistical approaches. It should be noted that only GDM works have been included, due to their wider applicability, and the scope of the thesis being mainly focused in this kind of approach. In any case, it is highlighted that many of the previous investigations falling within the AADM category contained in Table 2-2 leverage some of the statistical results obtained in the GDM works that are analysed here, further highlighting the reusability of these research efforts.

Table 7-1. Summary of previous statistical analysis works on the domain of RPA vehicle design. When a classification has been employed to group RPAS to extract different trends for each of these categories, this has been highlighted.

Authors	Year	Sample size	Main contributions and used classifications
Sóbestor et al. (15)	2005	30	Regression for the OEW/MTOW fraction for RPAS. Scatter plot for thrust-to-weight ratio and wing loading of RPAS and comparison with manned aircraft typical values.
Neufeld and Chung (35)	2005	N/A	Data mining approach to generate decision trees for configuration decisions, which are used along database figures in optimisation process.
Palmer (36)	2014	875	Histograms and scatter plots for general mass, wing, fuselage and performance and powerplant parameters, as well as categorical aspects. The main categorisation is based on the powerplant type.
Gómez-Rodríguez et al. (38)	2018	398	Discussion of trends of aerodynamic layout and powerplant use according to MTOW. Correlations for main parameters of wing, HTP and VTP for H-tail RPA. Use of categorisations based on general layout and powerplant.
Verstraete et al. (39)	2018	856	Correlations for main mass, wing and powerplant parameters, with use of a powerplant-based categorisation.
Aliaga-Aguilar (61)	2018	67	Use of factor analysis within the context of a pricing estimation approach for RPA.
Götten et al. (116)	2018	42	Correlations for wing, fuselage, tail boom, payload and landing gear parameters. Focus on Small and Medium Reconnaissance (SMR) RPAS.
Iqbal Bajwa et al. (45; 47)	2022/ 2024	41	Novel machine learning approach to extract design trends from the database of RPAS. Focus on overall mass, dimensions and performance parameters of the aircraft.
Mitridis et al. (40)	2023	202	Use of NATO classification of RPAS. Discussion of categorical variable trends. Scatter plots and regressions for general RPA performance, mass and wing variables. Analysis of scatter for certain parameters through box plots.
Agez (46)	2024	261	Focus on military classification of RPAS. Statistical regressions for general RPA performance, mass and wing variables. Development of rapid sizing method based on aforementioned empirical relationships.

As seen above, the majority of works in the domain of RPAS have employed descriptive statistics, scatter plots, and regression analysis to obtain general trends and empirical relationships on various RPA design variables. Due to the remarkable design diversity when considering the whole set of RPAS, many of these investigations have employed classifications to group the aircraft included in the database into more homogeneous groups, seeking to improve the results of the regressions. This connects with the topic of RPAS classifications and their advantages which was expounded in section 1.2 of this thesis. Here, it can be seen that the most extended classification is the one based on powerplant, albeit distinct works have also employed other criteria, arriving at different results in each case. Overall, the need of this process of grouping RPA in more

homogeneous sets is emphasised within previous research as a fundamental step to improve the representativeness of the statistical results (36; 38; 40).

However, this process of generating smaller sets of aircraft has a drawback in that it reduces the sample size of each of the groups. In some cases, the whole database collection process is focused on a particular type of RPA, such as in the research of (116) where only those within the SMR category were studied, which substantiates the lower sample size of this study. Overall, the number of aircraft included in each study varies significantly attending to various factors, such as the scope of the work, the type of results that are sought in each case, and also the difficulties related to RPA data gathering, which shall be further commented along this chapter. A relevant characteristic seen in all of the works is that they all develop their in-house databases. This is due to the lack of common publicly available datasets on RPA design information. Instead, each of the investigations included in the table above have to cover the step of compiling a database as part of their research efforts. These are usually constructed from reputable data sources such as the Jane's Unmanned Yearbook (37), as well as from scattered manufacturer's data available on the Web. This complicates a direct comparison among the databases employed in each of these studies.

The research studies which have mainly focused on the use of regression analysis would be those of (38; 39; 40; 46; 116). When compared to other investigations, these usually tend to present more comprehensive databases, not only with higher sample size, but also covering RPA pertaining to distinct groups. Therefore, these works also tend to employ classifications to obtain more accurate trends for each of the categories. Most of these works are focused on overall aircraft variables, such as *MTOW*, *OEW*, wingspan, b_w , or wing surface area, S_w . Only a few have included some typical values or regressions for the tail unit and for the relevant fuselage and tail boom dimensions at the conceptual stage.

At this point it should also be highlighted that other statistical works based on regression estimation also exist in the field of RPAS design which are not focused on the design of the overall vehicle itself. Two of these would be those of (156; 157), which are instead centred on powerplant sizing for RPA. As aspects related to the powerplant are also crucial within the overall RPAS design process, these present synergies with those which have been compiled here. However, as they are not focused on the vehicle itself, they would be considered outside the scope of this analysis.

Since factor analysis is one of the statistical approaches to be employed within this chapter, it is specially relevant to highlight the work of (61), which used factor analysis for the development of a pricing estimation method for small RPAS. The variables involved were mostly those describing characteristics of the overall aircraft. Albeit the mathematical results from the factor analysis approach were not directly used for the pricing estimation itself, the underlying trends that they unveiled were then used to perform a multiple regression where pricing could be obtained as the response variable.

Albeit other investigations using factor analysis for overall RPA or manned air vehicle design were not found in the open literature, this technique has been employed within the field of RPAS safety to aid in analysing accident trends (365) and risk of operations (366). It has also been used to measure the public's perception of the potential uses of RPAS (367). An application which, albeit outside the area of aeronautical engineering, has similarities to that which will be developed in this chapter, is the one presented in (368). It focuses on the application of factor analysis to the design of alloy tires, which seeks to obtain interrelations amongst the design parameters and the resulting mechanical properties. Overall, it can be seen that factor analysis constitutes a novel approach within the area of aircraft and RPA design, and therefore both its use and the development of a geometric sizing approach based on the obtained results would constitute original contributions of this chapter.

In contrast, it should be mentioned that the use of factor analysis is much more extended in other areas of research, particularly in social sciences. This can be explained as the origin of factor analysis can be found in the field of psychology (369), and these methodologies have experienced a notable expansion to other areas along the last century (370; 371). Most notably, recent studies have highlighted that they have been applied in over 1700 studies in the span of two years (371). Other recent studies have emphasized that they are also increasingly being applied in the area of engineering, which is characterized by low measurement errors in the different variables to consider (372). Some of the notable applications for other scientific disciplines can be found in the field of geology, in which the objective was to reduce the problem of study to a few factors that reveal the environmental conditions in a certain area (373). Factor analysis has also been employed in hydrologic studies, both for groundwater (374) and surface water (375). These studies also focus in reducing the dimension of the problem of study to the fundamental factors that affect a high number of observable variables, so as to economise the information collection (375).

Now going back to the specific area of statistical approaches for RPA design, there are others works which stand out due to their different approaches when compared to the others. On the one hand, the investigation presented in (35) constructs decision trees from a database compiled by the authors. These are mostly focused on configuration selection aspects, including powerplant type and location choices, which are related to cutoff values of various quantitative values as obtained from a data mining algorithm. Then, when designing a new aircraft and when the values of the quantitative variables are known, the choice on the qualitative aspects can be made. These decision trees are then implemented in an optimisation process, showcasing the usefulness of empirical relationships even in design frameworks which would fall within the preliminary design stage, according to the criteria used in this thesis as established in subsection 2.1.2. However, not all of the decision trees are provided in the paper, thereby difficulting the reuse of these statistical results in further research. On the other hand, the investigations of (45; 47), which are both part of the same line of research, assess the use of ML

algorithms to extract design trends for RPAS. After testing different approaches, the authors settled on the use of ANNs with two hidden layers, obtaining empirical relationships covering four design variables.

In view of the different studies mentioned beforehand, some gaps would remain which would aid in further advancing statistical approaches for RPAS:

- 1) The first is that only one of the works listed in Table 7-1, which is that of (38), has employed a classification based on aircraft overall layout. As commented in chapters 2 and 4, distinct aircraft layouts can potentially result in dissimilar design trends, even when focusing on the type of tail, and the analysis of the specific design aspects of different configurations was highlighted in previous works as a future need for the field of RPAS design, particularly considering their layout diversity (21; 33). It is noted at this point that the research presented in (38) has been conducted with a previous version of the database which has been then expanded and used within this thesis.
- 2) Furthermore, most previous works do not extract typical values or trends for the tail surfaces, fuselage, and tail booms. As commented in chapters 2 and 6, this does not only result in a gap within statistical approaches itself, but it also influences the development of overall initial sizing approaches that include the design of the tail units. This is in contrast to statistical approaches in manned aircraft design, which usually place a strong emphasis on obtaining results for fuselage and tail surface sizing (42; 44; 104; 360). Thus, this constitutes a particular gap within the area of RPA, and addressing it also has an effect in design approaches with a broader scope such as overall initial sizing methods and even computerised design environments, as discussed beforehand through the thesis.
- 3) Finally, considering the four steps usually followed by statistical works in the manned aeroplane design area expounded at the start of this section, previous research in the field of RPAS seldom arrive to the fourth point, which is in contrast to the case of the aeroplane design area. The only works proposing geometric sizing approaches from their statistical results for RPA would be those of (38) and (46). Certainly, the extraction of statistical trends from the database already has a remarkable value by its own. However, the integration of those results within a design workflow would constitute yet another steps towards enhancing these kind of approaches.

These gaps shall serve to establish the main directions of the research to be presented within this chapter. Considering this, the measurement and analysis of trends related to variables pertaining to the tail surfaces, fuselage, and tail booms shall be emphasised. Furthermore, the use of a classification based on general layout of the aircraft will be studied. This also fits with the attention that will be given to variables related to the tail unit as mentioned above. Additionally, the obtained results from both the regression

method as well as from the factor analysis one shall be employed to derive a geometric sizing approach aligned with those usually found in manned aeroplane design methods. These priorities shall also aid, linking with the discussion of chapter 6, to do these gaps in methods that have a broader scope, since they are influenced by the limitations of the building blocks used for their construction. In the context of this thesis, the impact on further chapters is remarkable, as the aforementioned considerations will allow to perform an overall initial sizing of the aircraft, including the tail surfaces, when developing the multi-role design method to be expounded in chapter 9. It will also permit to propose a configuration selection approach within the combined design approach that will be developed within chapter 10.

7.3. Overview of fundamental statistical concepts

In this section of the thesis, a series of statistical concepts will be expounded which lay the fundamental basis of the mathematical development pertaining to both the theory of regression analysis and also of factor analysis. This will allow for future subsections 7.4.1 and 7.4.2, to focus expressly on those aspects that concern the subjects of these disciplines themselves. The text below shall mainly focus on practical aspects, with the full development of the related concepts being found in the references which have consulted to write this section, these being (376; 377; 378).

Before moving on to more specific subjects, some general notions and considerations are introduced here. The research developed in this chapter covers three types of statistical approaches:

- 1) **Univariate methods**, such as when obtaining a histogram to describe the trend of continuous or categorical variables.
- 2) **Bivariate methods**, for instance when estimating the simple linear regression between two variables.
- 3) **Multivariate methods**, with multiple regression and factor analysis being examples included within this chapter.

A distinction is also made between dependence methods and interdependence methods. The first ones are focused on the association between two sets of variables, with one usually being the predictor variables, and the other the response variables, where the first ones are the ones used to estimate the values of the second ones. Regression analysis would fall within this group. In contrast, interdependence methods study the mutual associations across all variables, without making distinctions between variable types. They usually emphasise the study of the underlying structure of the data, usually through data reduction, rather than prediction. Factor analysis would fall within this second group (377).

Additionally, the concepts of observational data and experimental data are introduced here. The first refers to that situation in which the experimenter has no control over the values of the variables included in the dataset. In contrast, the second scenario presents itself when the experimenter can control some of the values (376). In the case of this work, as the data is compiled from existing RPA, the research would fall within the first category.

Finally, a relevant distinction is highlighted between the concepts of population parameters and sample statistics, which is made as follows: “A *parameter* is a numerical characteristic of a population or process. A *statistic* is a numerical characteristic that is computed from a sample of observations” (378). The first ones are usually designated using the greek alphabet, whereas the latin alphabet is typically employed for the second ones (378). From a practical standpoint, the results obtained from the database are applicable to the sample included within it. However, through the process of statistical inference, the statistics from the sample can be used to estimate values and trends pertaining to the whole population. Within the context of this work, this constitutes a crucial aspect, as if the results obtained from the statistical analysis are to be employed to size a new aircraft, this new design would represent an aeroplane which is not within the sample of the database. Thereby, metrics and analyses to ensure the adequacy of the inference process shall be taken into account through this work.

7.3.1. Corrected and standardised variables

One of the foremost steps that will be used throughout this chapter consists in the correction and standardisation of the variables to be studied. This process seeks to convert any random variable into another one which has null mean and unit variance. Before correcting and standardising a certain variable, it is first needed to obtain its mean and variance through the following expressions:

$$\text{Mean (population):} \quad \mu_j = \frac{\sum_{i=1}^n x_i}{n} \quad [7-1]$$

$$\text{Mean (sample):} \quad \bar{X}_j = \frac{\sum_{i=1}^n x_i}{n} \quad [7-2]$$

$$\text{Variance (population):} \quad \sigma_j^2 = \frac{\sum_{i=1}^n (x_i - \mu_j)^2}{n} \quad [7-3]$$

$$\text{Variance (sample):} \quad s_j^2 = \frac{\sum_{i=1}^n (x_i - \bar{x}_j)^2}{n - 1} \quad [7-4]$$

$$\text{Typical Deviation (population):} \quad \sigma_j = \sqrt{\sigma_j^2} \quad [7-5]$$

$$\text{Typical Deviation (sample):} \quad s_j = \sqrt{s_j^2} \quad [7-6]$$

Where n represents the number of individuals in the sample, the subscript i refers to the index associated to the individuals, and the subscript j identifies a specific variable of the dataset. The first expression in each pair represents the population parameters of the parameters, and the second one is related to the sample statistics. In the scope of this work, the individuals shall be each of the RPA included in the database.

Once the above values are known, the following expression is used to express the value of the random variable x_j for each of the individuals in a corrected and standardised format:

$$z_i' = \frac{x_i - \bar{x}_j}{\sigma_j} \quad [7-7]$$

There are various advantages when expressing variables in this format. Firstly, it allows the results of the statistical operators of mean and variance to be, respectively, zero and unity. This makes it possible to simplify certain expressions into a much simpler format, as will be seen further along this chapter. Another advantage is that variables that have a very wide range of values will be equated with those with smaller ranges. For example, the *MTOM* values for different RPAS in the database to be presented later on this chapter cover a wide range, from a few kilograms (such as AeroVironment's RQ-20 Puma, with a mass of 6 kg) to thousands of kilograms (such as the RQ-4 Global Hawk, with an *MTOM* value greater than 12000 kg). In contrast, other variables, such as the surface area of the horizontal stabilizer, S_h , can usually vary from a tenth of a square meter to several units of square meters. Therefore, this system allows both variables to be rescaled so that their ranges of values are comparable.

7.3.2. Covariance and correlation matrices

One of the fundamental steps of the factor analysis procedure consists in obtaining the covariance and correlation matrices between the different variables involved in the study. Covariance measures the proportion in which changes are observed in one variable in the face of modifications in another. Its expression is given by:

$$\text{Covariance (population)} \quad \sigma_{xy} = \frac{1}{n} \sum_{i=1}^n (x_i - \mu_x)(y_i - \mu_y) \quad [7-8]$$

$$\text{Covariance (sample)} \quad s_{xy} = \frac{1}{n-1} \sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y}) \quad [7-9]$$

Where in this case, x and y are used to identify two distinct random variables. Again, the first expression corresponds to the population value and the second one to the statistic of a given sample, which can also sometimes be designated c_{xy} . In addition, it should be noted that variance precisely represents the covariance of a variable with itself.

By arranging the calculated covariances between various variables in a matrix, with the variance values diagonally, this is called the covariance matrix, C .

Next, the concept of correlation will be addressed, which is usually expressed as Pearson's correlation coefficient. This coefficient has a series of distinct statistical interpretations, which are fully expounded in (379). Its classic expression for a sample is as follows:

$$r_{xy} = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2 \sum_{i=1}^n (y_i - \bar{y})^2}} = \frac{s_{xy}}{s_x s_y} \quad [7-10]$$

Where it is seen that this coefficient can be interpreted as a standardised covariance (379) when reaching the second expression by substituting the values of variance and covariance and simplifying the sample size. Thus, the value of this coefficient ranges from -1 for a direct inverse relationship to +1 for a direct relationship.

If a matrix is built with the values of the correlation coefficient for each pair of variables, it is called the correlation matrix, R . Since the values of the variance of each variable were on the diagonal of the correlation matrix, dividing by the deviation of that variable twice yields a unit value, so one of the characteristics of this matrix is having ones in its diagonal.

Since the topic of statistical regression will be discussed below, it is also noteworthy to highlight at this point that, in the case of a simple regression, the value of the coefficient of determination R^2 will coincide with the square of Pearson's correlation coefficient.

Finally, it is noted that both the C matrix and the R matrix are symmetrical, a property that will be crucial to be able to develop certain factor extraction techniques.

7.3.3. Hypothesis testing

In the field of statistics, hypothesis testing is a technique that is often used when making statistical inference assumptions. As mentioned beforehand, statistical inference consists in drawing conclusions about the global population from the results obtained from a sample. However, these conclusions will be affected by a certain error, since no matter how large the sample is, information is being lost by studying only a portion of the set of individuals from whom significant conclusions are to be drawn.

In this way, hypothesis testing consists in comparing two propositions, the null hypothesis, H_0 , and the alternative hypothesis (H_a). In the context of the research conducted in this chapter, these will usually consist in assumptions about the value of a population parameter based on the data obtained for its corresponding sample statistic. The null hypothesis usually refers to a situation in which there is no experimental effect, and the alternative hypothesis refers to an scenario in which there is a change from what was previously assumed (378; 380).

A classic example is to assume that a certain variable, labelled x , follows a normal probability density function with mean μ_x and standard deviation σ_x . The classic notation to indicate that the random variable x follows this distribution is:

$$x \sim N(\mu_x, \sigma_x) \quad [7-11]$$

A sample set of observations is taken for this variable, thus the sample average $\bar{x}$ is known. Now, the objective is to make assumptions about the value of the population mean. In this case, the estimator used to obtain the population mean, under the assumption that the population standard deviation is known, is given by:

$$T = \frac{\bar{x} - \mu_x}{\sigma_x / \sqrt{n}} \sim N(0,1) \quad [7-12]$$

Where the statistic follows a standardised normal distribution, that is, it has null mean and unit variance, being analogous to the case of corrected and standardised random variables. Using the probability density function of the distribution, and introducing the value of the estimator, the associated probability can be obtained.

The null hypothesis in this experiment would be that $H_0: \mu_x = 0$, while the alternative, which is usually the one that is sought to be demonstrated, is that, in view of the value of the sample mean, $H_a: \mu_x \neq 0$. Thus, considering the null hypothesis, the value of $\mu_x = 0$ would be substituted in [7-12], and since the distribution followed by the estimator is known, the value of the estimator under this hypothesis can be obtained.

To perform the hypothesis test, the p-value method will be used. The statistical significance of the p-value consists in the probability of observing a value of the statistic that is as extreme, or more extreme, than the one observed when assuming that the null hypothesis is true (378). Thus, in this case, it would be the value of the probability given by the corresponding probability density function on the tail defined by the estimator T .

Thus, if the observed value of the statistic is very close to the extreme of the probability density function, the p-value will be small, which means that it is unlikely to observe values of the statistic that are more extreme with respect to this case. Since this test is done assuming the null hypothesis, a low p-value means that it is unlikely to observe, if this hypothesis is verified, the result that has been obtained. Thus, this may mean that it is necessary to reject the null hypothesis because of the difficulty of finding such a value of the statistic, and then the alternative hypothesis is accepted.

Although it can be seen that the null hypothesis can be rejected with a higher degree of confidence for lower probabilities associated to the p-value, it would be necessary to establish a numerical cutoff criteria to employ this criteria in a systematic manner. At this point, the concept of the significance level, α , is introduced, which is defined as the maximum accepted probability of rejecting the null hypothesis when, in reality, the null hypothesis is true. In statistics this is known as a Type I Error.

Thus, for smaller accepted errors, the observation must be more extreme so that the obtained p-value falls below the limit set by the level of significance. Depending on the type of hypothesis test that is considered (one-tailed test in the case of considering the

error only in one of the directions, or two-tailed in the case of applying the confidence interval on both sides), the limit value of the probability that will be accepted will be α for the unilateral test and $\alpha/2$ for the two-tailed test, as the probability must be distributed between the two regions of error. Figure 7-2 illustrates the way in which the confidence interval is represented for a two-tailed hypothesis test. As can be seen, the corresponding probability value would be $\alpha/2$ for each side.

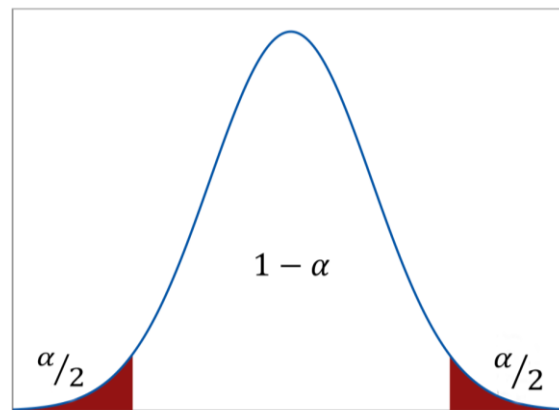


Figure 7-2. Two-tailed hypothesis testing corresponding to a normal distribution Image retrieved from: <https://online.stat.psu.edu/statprogram/book/export/html/524>.

Depending on the statistic being studied, the distribution that its estimator will follow may change, and it can therefore be represented by a probability density function that is not the normal one. In each case, the function of the probability should be calculated will be discussed.

With respect to the selection of the significance level, the most common values considered in the open literature are 10 %, 5 % and 1 %. In the case of this thesis, which aims to develop a conceptual design methods for RPAS, a value of 5 % is selected, which is considered to strike an adequate balance. This value is sufficiently low so that the error of the design methodology is not too large. Albeit a larger margin of error is usually accepted in conceptual design approaches when compared to further stages, with different works stating values between 10 % and 20 % (7; 8; 9; 14; 48; 61), it is still required that the initial aircraft concept generated through these approaches constitutes an approximate representation of the final aircraft. Therefore, a value lower than 10 % is selected. On the other hand, if a low value of the significance level is selected, this means that it will be more difficult to achieve statistical results that comply with it. As outlined in the introduction to this chapter, and as it will be seen in more detail within section 7.5, there are significant hurdles faces in the development of statistical approaches for RPA design, including a comparatively high scatter when compared to manned aircraft, and difficulties in finding accurate sources of information. Thereby, the value of 1 % is considered too restrictive. With all of this, striking a compromise between both types of

considerations, a significance level of 5 % is selected for the remainder of the studies to be carried out during this chapter.

7.4. Materials and methods

This section expounds the main materials and methods to be employed in the statistical analyses and in the proposal of the geometric sizing approaches that will be conducted in sections 7.6 and 7.7.

With respect to the methodologies, these include both the regression analysis approach, which is expounded in subsection 7.4.1, as well as the factor analysis one, developed in subsection 7.4.2. It should be noted that the latter requires the use of concepts from regression analysis for its development, so all necessary information in this regard is also provided in the subsection dealing with regressions. As the use of regressions is more extended in aeroplane conceptual design studies when compared to the factor analysis approach, the latter shall be developed in more depth, since it is an atypical methodology which has not seen previous extended use in this area of study.

On the other hand, the main material that will be used along with both methodologies is the RPA database which has been compiled as part of this thesis, and which is used as a basis for the estimation of statistical results. Subsection 7.4.3 provides the fundamental information on the database compilation process, as well as an overall descriptive overview of its contents.

7.4.1. Regression analysis

Statistical regression is a dependence method which seeks to estimate a model that allows to predict a response (or outcome variable) from a set of predictor variables. Regression models receive various names depending on the kind of mathematical model used to fit the data, which can be linear, polynomial, potential, or logarithmic, among many others (376). Furthermore, there is a distinction between simple and multiple regression, with the first being the particular scenario in which a single predictor variable is used, thus falling within the category of bivariate statistical approaches; whereas multiple regression is considered as a multivariate technique (377).

The first key element to enable the use of regression analysis is the availability of data itself. The values of both the response variable as well as those of the predictor(s) one(s) must be known for a series of individuals, which constitute the sample of the analysis. The characteristics of the model related to inference are affected both by the sample size, with a larger size benefitting to extract conclusions about the population; as well as by the results of the model itself, including the values of its statistics, among other aspects. The second element to apply regression analysis is the method to estimate the coefficients of the model so that it fits the observed data, with the least squares method being the most

frequent one (376). Then, a series of analyses can be conducted on the model which has been obtained, so as to assess its quality and associated inference capabilities.

A complete exposition on the subject of statistical regression models is reflected in numerous references within the open literature, such as those of (376; 378). In this subsection, the focus shall be on the practical aspects and expressions necessary to obtain the regression model from a dataset. The different metrics related to regression quality and to the possibility of inferring conclusions about the population of study will also be highlighted. Additionally, it should be noted that most of the text below has been formulated according to the case of multiple regression, since this scenario is reduced to the one corresponding to simple regression by assuming a single predictor variable. Finally, it is also clarified that the process detailed here is formulated attending to a linear multiple regression case. The adaption of this formulation to other models, such as polynomial or potential ones, only requires minor additional considerations, which are covered in reference (376).

(a) Estimation of multiple regression

In the case of a multiple linear regression, the form of the model is given by:

$$\hat{y}_i = b_0 + \sum_{j=1}^p b_j x_{ij} \quad [7-13]$$

Where the coefficient b_0 represents the intercept of the model, the coefficients b_j are the slopes accompanying each of the p predictor variables of the model, x_{ij} represent the p predictor variables themselves, and $\hat{y}_i$ is the predicted response by the model.

The least squares methods obtains the coefficients of the model via minimising the Sum of Square Errors (SSE), also called Sum of Square Residuals. Its expression is given as follows:

$$SSE = \sum_{i=1}^n (y_i - \hat{y}_i)^2 \quad [7-14]$$

Where y_i is the observed response of the variable as contained in the dataset, and the subscript i indicates that the summation is evaluated for every individual in the sample, thus comparing the real response with the one estimated by the regression model.

To obtain the coefficients of the multiple regression model through the least squares method, equation [7-13] is introduced in [7-14], and this latter expression is minimised to obtain the coefficient estimators. With this, the system of normal regression equations is obtained (378). It is a system of $p+1$ equations, one for each coefficient of the model. It should be noted that it is essential that the size of the sample is at least equal to $p+1$ for this system to have a unique solution. Otherwise, the resolution of such a system fails,

which is a key aspect that also affects the factor analysis approach as it will be seen in the following subsection. From a practical standpoint, this will result in a restriction in the selection of the number of variables that can be studied for a given sample, which is particularly critical considering the low sample size that in certain scenarios of the factor analysis application to the RPA database, as it will be seen in section 7.7.

A matrix procedure to solve the system is developed in (376) and (381). In this way, the vector of coefficients can be obtained from the following expression:

$$\vec{b}_{(p+1) \times 1} = (T'_{(p+1) \times n} T_{n \times (p+1)})^{-1} T'_{(p+1) \times n} y_{n \times 1} \quad [7-15]$$

Where:

- $\vec{b}_{(p+1) \times 1}$ is the vector of the b_j coefficients that accompany each of the variables plus the independent term.
- $T_{n \times (p+1)}$ is a data matrix, with the rows corresponding to different individuals of the sample, and the columns containing the observed values of the predictor variables for each of the individuals, except for the first column, which is filled with unitary values, as it is intended for the calculation of the independent coefficient.
- $y_{n \times 1}$ is a data vector, containing the observed values of the response variable for the n individuals.

(b) Regression metrics

Once the estimators for the sample statistics of the regression coefficients have been obtained, the quality and inference capabilities of the regression model can be assessed through a series of metrics. The steps followed to obtain these metrics are often considered within the Analysis Of Variance (ANOVA) procedure (376; 378).

Firstly, aside from the aforementioned SSE, there are other two measures of variations represented by two additional Sums of Squares (SS). These are the Regression Sum of Squares (SSR), also called model sum of squares, and the Total Sum of Squares (SST), which are given by the following equations:

$$SSR = \sum_{i=1}^n (\hat{y}_i - \bar{y})^2 \quad [7-16]$$

$$SST = \sum_{i=1}^n (y_i - \bar{y})^2 \quad [7-17]$$

Where $\bar{y}$ is the average of the values of the estimated variable as contained in the dataset.

It can be seen that the SST value corresponds to the numerator of the total variance of the variable, as seen in equation [7-3]. Therefore, a part of this total variance is accounted for by the regression model, and if the data points fell exactly on the regression surface, SSR and SST would match. However, there is a certain component of error in the model, which corresponds to the residuals of the variable y . These are the differences between the value that is predicted by the regression surface, $\hat{y}_i$, and the actual value observed in the dataset, y_i . The difference between these two values represents the portion of the variance of variable y that is not accounted for by the regression model, which was the variable being minimised through the least square methods, as the difference $\hat{y}_i$ and y_i appears in the equation of SSE as seen in [7-14].

Equations [7-14], [7-16], and [7-17] are expressed in algebraic formulation. For the case of a multiple regression application case, these can be rearranged into matrix form in the following way, where the meaning of the different symbols are as commented beforehand through the text:

$$\text{Regression:} \quad SSR = b'T'y - \frac{1}{n}(1'y)^2 \quad [7-18]$$

$$\text{Residuals:} \quad SSE = y'y - b'T'y \quad [7-19]$$

$$\text{Total:} \quad SST = y'y - \frac{1}{n}(1'y)^2 \quad [7-20]$$

Once the values of the different SS are known, the next step consists in obtaining the Mean Square (MS) metrics, which are a general application of the concept of variance. Their general expression is given as follows:

$$MS = \frac{SS}{df} \quad [7-21]$$

Where SS represents the corresponding sum of squares, and df is the value of the Degrees of Freedom (DOF) associated with the applicable SS .

The degrees of freedom of an statistic are associated with the number of sources of variance associated to it. These are generally obtained as the difference between the sample size of the model, n , and the number of estimated parameters, l , included in the mathematical expression of that estimator (382). This is the reason for the $n-1$ expression found in the denominator of the sample variance, equation [7-4], with a degree of freedom being lost due to the population mean being estimated using the sample mean. This particular correction for sample variance is called the Bessel Correction.

In the case of multiple regression, the degrees of freedom associated with the regression correspond to the number of independent variables used in its estimation, with this value

being p as seen beforehand. The degrees of freedom associated with the residuals are given by $n-p-1$, this is, the number of predictor variables and an additional unit corresponding to the independent coefficient are subtracted from the sample size. The value of the degrees of freedom associated with the total sum of squares would be $n-1$, precisely because of the influence of the sample mean as mentioned above.

Thus, the mathematical expressions of these MS metrics are:

$$\text{Regression:} \quad MSR = \frac{\sum_{i=1}^n (\hat{y}_i - \bar{y})^2}{p} \quad [7-22]$$

$$\text{Residuals:} \quad MSE = \frac{\sum_{i=1}^n (y_i - \hat{y}_i)^2}{n - p - 1} \quad [7-23]$$

$$\text{Total:} \quad MST = \frac{\sum_{i=1}^n (y_i - \bar{y})^2}{n - 1} \quad [7-24]$$

It can be seen that these statistics represent the variance associated with the estimated variable as a whole, which can be broken down into the variance accounted for by the regression, and that which is associated to the differences (residuals) with respect to said model.

Once the aforementioned values are available, the metrics to evaluate the quality of the regression model can be obtained. The most widespread metric of these is the so-called coefficient of determination, R^2 . Its general mathematical expression is given by:

$$R^2 = \frac{SSR}{SST} = 1 - \frac{SSE}{SST} \quad [7-25]$$

The meaning of this coefficient, as it can be seen from the previous equation, is to assess to what extent the regression established between the dependent and the independent variables accounts for the total variation observed in the estimated variable (378). It can also be interpreted through a different lens, quantifying the reduction in the remaining variance of the dependent variable when it is estimated through the use of the predictor variables (376). Thus, values close to unity mean that nearly the entirety of the variance of variable y has been accounted for when it is estimated through the variables x_j .

A different statistic which also has a significant relevance in the interpretation of the regression model is the so-called standard error of residuals, which is related to their standard deviation. In a broad sense, the concept of typical error of a sample statistic is associated to the standard deviation of its sample distribution (378). In the case of regression analysis, this error is given by the square root of the MSE, as this latter metric precisely represents the variance of the residuals. Thus, the standard error applied to this called is also called Root Mean Square Error (RMSE), obtained through the following expression:

$$s_e = \text{RMSE} = \sqrt{MSE} \quad [7-26]$$

Comparing the order of magnitude of this metric with that of the typical values of the dependent variable can allow to check whether the deviations of the observed values with respect to the regression model are significant, which could call into question the validity of the regression. Therefore, it is key to consider this value alongside the coefficient of determination to permit a more thorough assessment of the regression model, which should be complemented by the hypothesis testing procedures commented below.

(c) Hypothesis testing for regression coefficient values

Once the coefficients that define the multiple regression have been obtained, a series of hypotheses tests can be proposed to estimate the applicability of the results from the sample to the whole population. As mentioned at the end of subsection 7.3.3, this is especially relevant in view of the prospect of applying the regression models to the sizing process of a new aircraft, as this aircraft concept will not belong to the sample of study contained in the database.

In the case of each of the coefficients that accompany the model's predictor variables, hypothesis testing can be carried out in the following manner. H_0 considers that the population value of the coefficient is zero, thus being $\beta_1=0$. This means that changes in the predictor variable would not trigger any change in the response of the model. In contrast, the alternative hypothesis H_a will consider that the above-mentioned assumption is not true, and that there is a significant value of said population coefficient $\beta_1 \neq 0$, thus the value of the response shall be influenced by the corresponding predictor variable.

To conduct this hypothesis test, the following statistic will be used (376):

$$t^* = \frac{b_j - \beta_j}{s\{b_j\}} \sim t(n-p) \quad [7-27]$$

Where this statistic follows a t-student distribution with the degrees of freedom being $df=n-p$, which corresponds to the sample size minus the number of variables of the model. The denominator of the statistic contains the standard deviation of the sample statistic of the corresponding coefficient, with this being precisely its standard error. This is different to the standard error of the residuals, of which there is only one for the full regression model as it was seen in equation [7-26]. In contrast, there is a value of standard error $s\{b_j\}$ for each of the regression coefficients. Their values can be obtained by using the following expression:

$$s\{b_j\} = s_e \sqrt{(T'T)^{-1}_{jj}} \quad [7-28]$$

Where s_e represents the typical error of the regression residuals, obtained according to equation [7-26]. The root of equation [7-28] contains the corresponding term of the diagonal of the indicated data matrix. It is demonstrated in reference (376) that the square of the elements of this matrix, when multiplied by s_e , allow to obtain the standard deviations of each of the coefficients of the regression model.

In this way, once the value of the statistic has been calculated, a two-tailed hypothesis test can be applied. The limit probability corresponding to the p-value of the estimator should be at the most $\alpha/2$ in order to reject the null hypothesis and therefore accept the alternative hypothesis. This latter scenario implies that the population coefficient associated to this variable would be statistically significant, and therefore that this predictor variable effectively has an impact on the response variable.

(d) Correcting and testing assumptions for R^2 value

According to the definition of R^2 proposed in equation [7-25], when adding predictor variables to the model, the SSE value would always be reduced, even if these variables only account for a small portion of variance of the dependent variable. Furthermore, the SST value would remain constant, since it depends only on the dependent variable itself (376). This means that, in any case, when adding more predictor variables to the model, R^2 would always increase, potentially leading to values arbitrarily close to 1 which do not really represent the goodness-of-fit (378).

To avoid this phenomenon, the corrected coefficient of determination $\widetilde{R}^2$ is defined, which will adjust the value of R^2 taking into account the increase in the number of predictor variables relative to the total number of observations. This correction is applied to each of the SS by using their respective degrees of freedom, following the equation below:

$$\widetilde{R}^2 = 1 - \frac{SSE/n - p - 1}{SST/n - 1} = 1 - (1 - R^2) \frac{n - 1}{n - p - 1} \quad [7-29]$$

Thus, if the reduction in SSE that is achieved through the integration of new predictor variables does not compensate the decrease in the denominator associated to the reduction in the degrees of freedom that results from integrating more predictor variables, then the value of $\widetilde{R}^2$ will not improve. Another key use of this $\widetilde{R}^2$ is that it can be employed as a better estimator of the population value of the coefficient of determination (381).

At this point, some further comments are made on the behaviour of $\widetilde{R}^2$ which shall be key through the analyses conducted in this chapter. As it will be seen through the application cases of both the regression and factor analysis approaches, in many cases the aircraft sample size values will be relatively small. It has already been seen that a reduced value of n penalises most of the results and estimators seen so far, but in the case of $\widetilde{R}^2$ the effect is more dramatic. Here, it is seen that if the sample size is only one more than the number

of variables, the value of $\widetilde{R}^2$ would be undefined. This coincides with the limit case which was mentioned beforehand of having a sufficient number of observations to solve the system of normal regression equations. Therefore, those cases where $\widetilde{R}^2$ would be undefined represent, in the first place, unfeasible scenarios of the multiple regression equation system.

Considering the above, the limit case for being able to solve the system of equations, as well as for obtaining feasible values of $\widetilde{R}^2$, is the scenario where the sample size contains at least two more individuals than the number of variables considered for the study. Albeit in most cases where large datasets are managed this does not constitute a typical scenario, it will be seen in the study conducted within this chapter that the low data available on certain RPA variables results in cases close to this limit one, which is the reason for introducing this aspect here. Further details on the challenges of RPA statistical analysis, which result in these scenarios with low sample sizes, are given in section 7.5.

To illustrate the behaviour of $\widetilde{R}^2$ when considering variations in both the number of variables and in the original coefficient of determination R^2 with a fixed sample size, Figure 7-3 represents its calculation for a sample of $n=10$ individuals.

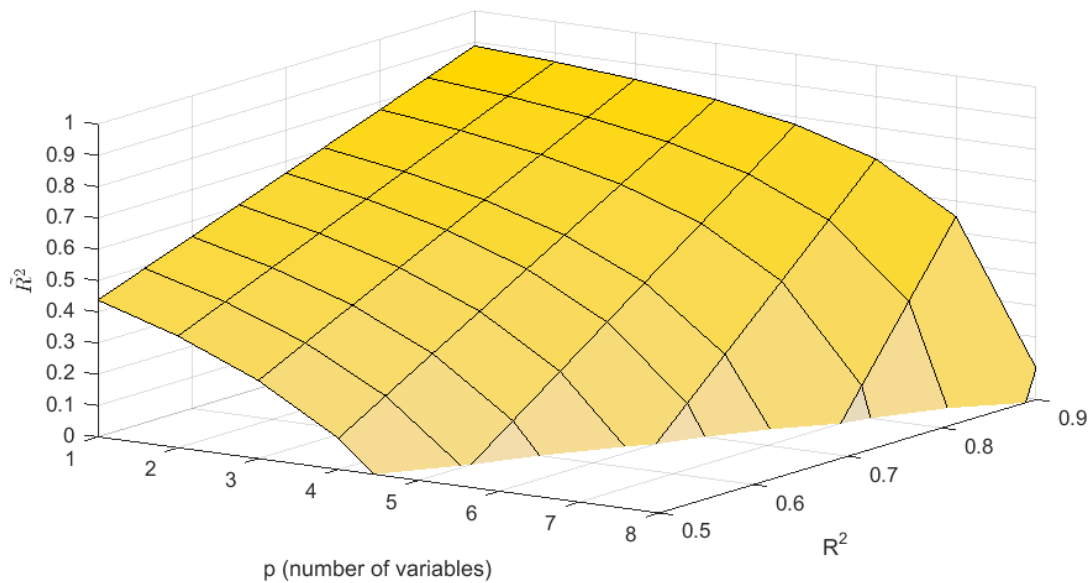


Figure 7-3. For a fixed sample size of $n=10$, the evolution of the corrected $\widetilde{R}^2$ value is calculated for different numbers of predictor variables and for distinct values of the original R^2 .

It can be observed that, as the number of variables increases while keeping the sample size fixed, there is an accelerated decrease in the value of $\widetilde{R}^2$. This decrease in the adjusted coefficient of determination is slowed down when higher values of the original R^2 are present, as these correspond, in a broad sense, to regressions with a higher degree of fit to the data. The locus of points in which $\widetilde{R}^2$ crosses the plane of zero ordinate represents

scenarios where the population correction represented by $\widetilde{R}^2$ does not represent feasible values.

To avoid these situations, a hypothesis testing for the value of $\widetilde{R}^2$ can be used, which seeks to verify the existence of a sufficiently strong relationship between the predictor variables and the dependent variable in the whole population and not only within the sample (376). The null hypothesis in this case corresponds to the fact that all the population coefficients that accompany each of the predictor variables are simultaneously zero, which represents the scenario in which there is no correlation. This is given by:

$$H_0: \beta_1 = \beta_2 = \dots = \beta_p = 0 \quad [7-30]$$

The alternative hypothesis corresponds to the fact that this scenario does not occur, so in that case, there would be a significant population regression, at least when accounting for some of the predictor variables. It is noted that this hypothesis test also has a more general relevance than its use here to analyse the feasibility of the $\widetilde{R}^2$ values, as in some cases, it is worth to focus on the overall model rather than on single coefficients, which was the case covered by the hypothesis test represented beforehand in equation [7-27]. The hypothesis test corresponding to equation [7-30] is given, in this case, by the following statistic:

$$F^* = \frac{MSR}{MSE} = \frac{n-p-1}{p} \frac{R^2}{1-R^2} \sim F(1-\alpha, p, n-p-1) \quad [7-31]$$

This statistic represents the portion of variance explained by the regression model when compared to the part of the variance that is not explained through it. It follows an F-Fisher distribution, whose overall degrees of freedom are set by those of the MSR in the numerator, p , and the ones associated to the MSE in the denominator, $n-p-1$. In this case, the hypothesis test is one-tailed. Since the total area under a probability density function must be unitary, the value $1-\alpha$ represents the portion of probability to the left of the observed value F^* , while the probability remaining at the tail of the distribution is α . Therefore, for F^* values close to unity, the null hypothesis is strongly supported by the result (which would mean that no population regression exists), while very high values of this statistic support the alternative hypothesis (meaning that a population regression seems to be feasible).

If the MSE value is close to null, which happens when the regression explains most of the overall variance, the result of the statistic tends to an infinite value. In this case, the area to the right of the value of the statistic would be very small, so the probability of making a Type I Error is low, meaning that inferences on the population can be made with a higher confidence. By checking this hypothesis test before calculating the value of $\widetilde{R}^2$, the Type I Error probability can be quantified. With this, if the null hypothesis can be rejected, the value of $\widetilde{R}^2$ can be guaranteed to have a reasonable result, thus allowing to obtain a feasible value for the population estimate of the coefficient of determination.

There is a relationship between this hypothesis test, which considers the regression model as a whole; with the one corresponding to equation [7-27], which is instead focused on each different correlation coefficient. This connection occurs in the particular case of a simple linear regression, where there is a direct equivalence between both tests. It is demonstrated in (376) that the value of the F^* statistic for one-tailed hypothesis testing is equivalent to the square of the value of the t^* statistic for two-sided hypothesis testing, considering the same level of significance α :

$$F^* = (t^*)^2 \quad [7-32]$$

This relationship can be explained when considering that, if the slope of the line associated to the only predictor variable in this case is zero, this means that the variance of the estimated variable is not explained by the predictor variable, thus the value of the coefficient of determination R^2 will also be null simultaneously. Therefore, when it comes to a simple linear regression, this equivalence can be applied and the hypothesis test can be approached by either of the two alternatives, since the result in terms of acceptance or rejection of the null hypothesis will be identical.

7.4.2. Factor analysis

The mathematical procedure of the factor analysis approach will be expounded in this subsection. The majority of the methodological process has been extracted mainly from references (370; 377). This has been complemented with some additional considerations which seek to take into account the particularities of the problem of study within the factor analytic process, which is that of RPA conceptual design. These adaptations constitute one of the original contributions of the methodologies presented within this chapter. One of these considerations is that the application of the factor analysis approach should allow to estimate the values of the different variables with an error of around 10%, so that is aligned with the typical magnitude of errors accepted in the aircraft conceptual design stage, as mentioned in 7.3.3. Furthermore, the scenario of managing data matrices with a low sample size shall also be taken into account, as it was brought forward in advance previously within this chapter that this will be the case of some of the analysis cases to be conducted later on. The issues related to data scarcity shall be further substantiated in section 7.5.

In view of the above, the contents of this subsection shall often refer to aspects related to the analysis application case of RPA design. The roadmap that will be followed in the description presented below is illustrated in Figure 7-4.

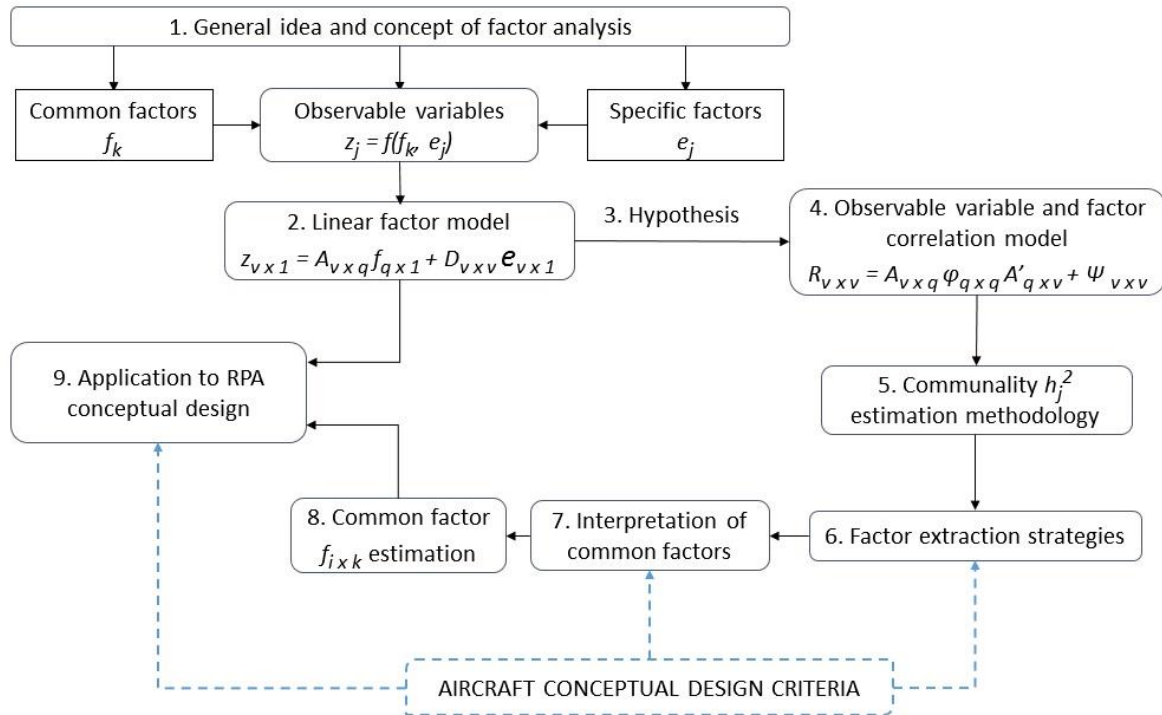


Figure 7-4. Factor analysis mathematical procedure roadmap. The steps of the process which are affected by particularities of aircraft conceptual design have been indicated. The meanings of the different variables and indexes shall be expounded further below in the main text.

(a) General idea and concept of factor analysis

As it was mentioned in the chapter's introduction, the objective of factor analysis consists in seeking a new set of variables, unobservable and less in number than the starting group, that expresses with significant fidelity the original interrelations amongst the observed variables. These observed variables could be, for instance, the wingspan, b , wing area, S_w or the area of the tail surfaces S_h and S_v . The aforementioned factors are divided into two groups. The first one is constituted by the common factors that account for the variance shared amongst the observable variables, and they are usually extracted on the basis of the regressions amongst the different variables, which represent their shared variance. Aside from these common factors, which influence all of the observable variables, each of the original variables is also described by a specific factor, which accounts for the portion of the variance that is not shared with the other variables (370; 377). The classic model of factor analysis assumes a linear relationship of the observed variables with the common and specific factors, loaded on a series of coefficients which must be estimated. This overall idea is summarised in the diagram of Figure 7-5.

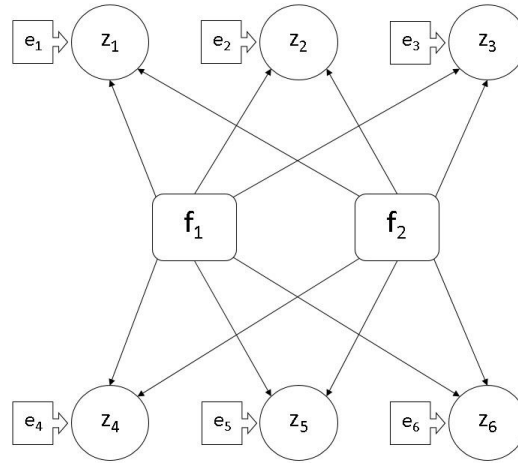


Figure 7-5. Summary of the factor analysis exposition. z_j represents the observable variables, in corrected and standardised format. Attending to the orientation of the arrows, the z variables are determined by both the common unobservable factors f_k , of which there are q in total, and by the corresponding specific factor e_j unique to each observable variable.

Accordingly, the result of this methodology can be interpreted as an information reduction technique, since the objective consists in expressing the observed variances in a set of variables, which in the case of this investigation would be the ones that describe the preliminary design of the aircraft, as a function of a reduced number of common factors. This type of methods is commonly referred to in statistics as parsimonious models. Effectively, one of the main contributions of a factor analytic model is the capacity to describe the majority of the observed interrelationships of a set of variables with a reduced group of factors.

Having presented the general idea behind factor analysis, some notation aspects which will be employed in the mathematical procedure that follows are listed below:

- **Subscript i:** lists the number of aircraft, where n is the total number of RPA of the sample.
- **Subscript j:** lists the number of observed variables (b, S_w, S_h, S_v etc.), with v being the total number of variables. This quantity matches the number of specific factors, as there is one for each of the original variables.
- **Subscript k:** lists the number of common factors f_k , where q is the total number of common factors extracted.

(b) Linear factor model

For the following description, the observable variables shall be presented in corrected and standardised form (having subtracted the mean and divided by the standard deviation). Likewise, both the common factors f_k as well as the specific ones e_j will be

considered as variables with zero mean and unit variance. Taking this into account, the previously mentioned linear model can be described with equation [7-33]:

$$z_{vx1} = A_{vxq}f_{qx1} + D_{v xv}e_{vx1} \quad [7-33]$$

where:

- z_{vx1} is the column vector including, for a particular aircraft, the values of the v variables in corrected and standardised form.
- f_{qx1} represents the column vector formed by the values of the q unobservable common factors for the aircraft of study.
- e_{vx1} is the column vector constituted by the values of the v unobservable specific factors (one for each of the observed variables) for the aircraft of study.
- A_{vxq} constitutes the matrix known as factor pattern, which contains the coefficients that accompany the common factors in equation [7-33].
- $D_{v xv}$ is the diagonal matrix which contains the coefficients that accompany the specific factors in equation [7-33].

Thereby, for each of the RPA within the database, the values of the z_j variables, the f_k common factors, and the e_j specific factors are different. However, the coefficients associated with the different factors will remain invariant.

(c) Factor and variable correlation hypotheses

For the following mathematical procedure, it will be assumed that the unobservable common factors that are extracted from the same data matrix are not correlated among them, that is, they are orthogonal. Furthermore, the specific factors will be considered to not be correlated amongst them neither with the common factors. Therefore, each of them shall be independent from the others. The consequence of these hypotheses will be that the unique part of each variable (determined by the specific factor loaded on the corresponding coefficient) will not be correlated with its common part (represented by the common factors) neither with the specific part of the other variables. Thereby, in the set of equations derived from equation [7-33], for each observable variable z_j the terms associated with the common factors shall not be correlated with the term related to the specific factor.

(d) Observable variable and factor correlation model

Having proposed the aforementioned hypothesis, the following step consists in arriving to an equation which links the values of the coefficients associated with the different factors with the correlation matrix of the observable variables. The mathematical

procedure to arrive to this expression can be consulted in reference (370), and the resulting equation would be the following:

$$R_{vzv} = A_{vxq} \Phi_{qxq} A_{qxv}^T + \Psi_{vzv} \quad [7-34]$$

where:

- R_{vzv} is the (symmetric) correlation matrix of the v observable variables, which in the case of the problem of study corresponds to the design parameters which will be used in the proposed RPA conceptual analysis procedure.
- Φ_{qxq} is the (symmetric) correlation matrix of the q unobservable common factors.
- Ψ_{vzv} is the (symmetric) covariance matrix of the v unobservable specific factors.

Considering the hypothesis regarding the orthogonality of the common factors, Φ_{qxq} shall be an identity matrix, since the non-diagonal terms represent the correlations amongst the common factors, which in this case are null. Ψ_{vzv} is also a diagonal matrix, since it has been assumed that the specific factors are uncorrelated. This matrix will contain in its diagonal terms the variances of the specific factors, which can be demonstrated match the squared corresponding terms of the D_{vzv} matrix (370; 377).

The next step will consist in analysing the variance of the model. Considering equation [7-33] and focusing on a certain variable z_j , the following expression is achieved:

$$z_j = \sum_{k=1}^q a_{jk} f_k + d_{jj} e_j = c_j + u_j \quad [7-35]$$

where c_j represents the common part of the variable, that is, the part, which is a function of the common factors, whereas u_j accounts for the specific part of the observed variable. Applying the variance operator on both sides of the equation, the following equation is obtained:

$$1 = \sum_{k=1}^q a_{jk}^2 + d_{jj}^2 = Var(c_j) + Var(u_j) \quad [7-36]$$

as it can be seen, the common variance of an observed variable can be expressed as the sum of squares of the elements of the corresponding row j of the factor pattern matrix. This value is designated as h_j^2 and is known as communality, with there being a communality for each of the j variables of the application case:

$$h_j^2 = Var(c_j) = \sum_{k=1}^q a_{jk}^2 \quad [7-37]$$

As mentioned at the beginning of the current subsection, one of the main contributions of this chapter is the inclusion of specific criteria related to the subject of aircraft conceptual design within the factor analytic process, so as to adapt it to the problem of study of RPA conceptual design. One of these criteria will be that the common factors should account for a high proportion of the total variance associated to the observable variables. The reason for this is that the geometric sizing approach that will be proposed in section 7.7 will allow to estimate the values of the common factors for the new RPA that is to be designed with the proposed method. In contrast, it will not be possible to obtain the values of the specific factors, so they shall be unknown. Therefore, in order for the values of the estimated variables to fall within the acceptable margin of error of conceptual design, it would be desirable that their communalities are close to 90 %, so that the uncertainty associated with the variance related to the specific factors falls within the acceptable margin of error. At this point, it should be highlighted that the limitation of the design method mentioned above refers to the values of the factors themselves, not to the values of the factor loadings, which can be obtained through the factor analysis process developed here for both the common and specific factors. Overall, the process proposed here constitutes a significant difference with respect to previous factor analysis studies, where the level of shared variance amongst the observed variables, and thus the portion of variance associated with the common factors, is usually lower than what will be seen in the RPA design case developed in this chapter.

On the other hand, the unique variance of each variable is noted as Ψ_j and known as uniqueness, and is determined, as it was previously mentioned, as the square of the corresponding element of the D_{vzv} matrix:

$$\Psi_j = \text{Var}(u_j) = d_{jj}^2 \quad [7-38]$$

These are precisely the elements that constitute the diagonal matrix Ψ_j from equation [7-34], and representing the specific variance of each observable variable. Similarly to the definition of the communality of each variable, the proportion of the variance accounted for by each common factor amongst that of all the variables also constitutes a relevant magnitude. This concept can be obtained with the following expression, which is similar to equation [7-37] but calculating the sum of squares of the column corresponding to the common factor in consideration:

$$V_k = \sum_{j=1}^v a_{jk}^2 \quad [7-39]$$

Therefore, the total variance accounted for by all the common factors can be obtained by adding the corresponding value of V_k for each factor q .

In order to apply certain factor extraction methods, it is necessary to estimate a preliminary value for the communalities h_j^2 . In equation [7-34], the correlation matrix

R_{vzv} is expressed as a function of both the pattern matrix A_{vxq} and the Ψ_{vzv} matrix, when considering the hypothesis of orthogonal common factors. Subtracting the Ψ_{vzv} matrix from the correlation matrix leads to the following expression:

$$R^*_{vzv} = R_{vzv} - \Psi_{vzv} = A_{vxq}A_{qxv}^T \quad [7-40]$$

where R^* is known as the reduced correlation matrix, which is identical to the correlation matrix except for the diagonal terms, which instead of being unit values, will be precisely the communalities of each of the observed variables, having subtracted from the total (unit) variance of the variable the value corresponding to its specific variance. Therefore, an estimation of the communalities will allow to undertake the procedure in order to obtain the elements of the pattern factor matrix. Once this matrix is known, it will be possible to check whether the estimation was adequate with the expression represented in equation [7-37].

(e) Communality estimation methodology

Various techniques can be found in the open literature to estimate the communalities in this first step. Three classical approaches include (377; 383):

- 1) Considering the highest observed correlation of each variable with the others as the communality estimate.
- 2) Obtaining the multiple correlation for each of the observable variables by using the remaining ones ($v-1$) as the predictors.
- 3) Using iterative methods which consist in extracting factors and employing the obtained communalities as estimations for the following iteration.

The method that will be employed in this research is the second, since it is the one most related to the mathematical significance of the concept of communality, that is, the portion of variance of each of the observed variables which is described by the common factors. Therefore, some authors propose to approximate the communality by the R^2 coefficient of determination resulting of the linear multiple regression of each variable as a function of the others (377). It must be noted that this approach has been considered as the most conservative one among the aforementioned three options, since it results in the lowest values for the communalities, thus being the lower bound for the population communality (371; 377; 383). The outcome of this is that the second approach produces common factors that account for lower portions of variance in the observable variables, leaving a higher proportion of variance unexplained by them.

Furthermore, an additional consideration has been undertaken here as part of the adaptations to the factor analysis process which are proposed in this chapter. This relates to the matter of taking into account the population correction of the coefficient of determination through the use of $\widetilde{R}^2$, as seen in equation [7-29] within the previous

subsection. This leverages the fact that a multiple regression is estimated within the second of the three approaches mentioned above, which is the one chosen. Therefore, the communality when accounting for this population correction would be represented by the value of the adjusted $\widetilde{R}^2$ instead of the one of the original R^2 . The expression for $\widetilde{R}^2$ which was already given in equation [7-29] is reformulated here attending to the notation used in this communality estimation step:

$$h_j^2 \cong \widetilde{R}_j^2 = 1 - \frac{SSE_j / (n - (v - 1) - 1)}{SST_j / (n - 1)} = 1 - (1 - R_j^2) \frac{n - 1}{n - v} \quad [7-41]$$

Here, it is seen that the communality of each of the v observable variables involved in the factor analysis process is obtained through a multiple regression using the other $v-1$ variables as the predictors. Thereby, the number of predictors of the regression, p , is equal to $v-1$, which has been accounted for in the equation above. Furthermore, the subscript j has been added to the equation in order to indicate that each observed variable has its own value of $\widetilde{R}^2$, which corresponds to its own estimated communality.

However, as expounded in subsection 7.4.1, before obtaining the value of $\widetilde{R}^2$ it is firstly required to check whether the population correction represented by this metric is feasible in itself. As expounded in the previous subsection, this is aligned with the existence of a significant relationship of the predictor variables with the dependent one not only within the sample, but also at the level of the population itself (376). Two hypothesis tests were presented in the previous subsection, with one being focused on each of the coefficients of the predictor variables [7-27], while the other assessed the overall fit when considering all predictors [7-31]. In this case, taking into account that the emphasis of the communality is on the variance of a certain variable which is already accounted for by the ensemble of the others, with the focus not being on the contribution of each of the individual predictors to the observable variable that is being considered, the second test would be the one that better fits this statistical interpretation. The F-statistic of this hypothesis test, which was given in equation [7-31] for the general multiple correlation case, has also been adapted to the notation employed in the communality estimation step:

$$F_j^* = \frac{MSR_j}{MSE_j} = \frac{n - (v - 1) - 1}{(v - 1)} \frac{R_j^2}{1 - R_j^2} = \frac{n - v}{v - 1} \frac{R_j^2}{1 - R_j^2} = \sim F(1 - \alpha, v - 1, n - v) \quad [7-42]$$

Thus, for each of the observable variables, it is first required to conduct the hypothesis test represented by the statistic given above. If the result falls within the inference metrics employed in the model, it can be supported that an adequate population correction of the coefficient determination exists, so the value of $\widetilde{R}^2$ is then estimated and this is used for the communality estimation for the corresponding variable, instead of the one corresponding to the sample.

This approach was not considered in previous factor analytic studies, most possibly since the sample sizes were sufficiently high so as to guarantee the statistical significance of the value for the multiple R^2 coefficient. However, as it has been brought forward in advance, and as it will be seen in section 7.7 once the factor analysis process is applied to the RPA database compiled as part of this thesis, the sample sizes that will be managed in this study, when compared with the number of observable variables, shall at times fall within challenging intervals for the application of factor analysis, as indicated by previous authors (371). This is the main reason for including this approach, which can be considered one of the particularities of the application of factor analysis to the RPA design problem of study.

(f) Factor extraction strategies

Having conducted the estimation of the communalities, the next step would be to apply the different factor extraction methodologies which have been developed in the open literature (370; 377). These procedures seek to determine the number of factors to be extracted, as well as their correlation with the observable variables, with this latter point being represented by the coefficients in the factor pattern matrix A_{vxq} . In this investigation, both the Principal Factor (PF) technique and the minimum residuals (often labelled “Minres”) approach have been employed, and a comparison between them has been undertaken.

The principal factor technique is based on the extration of consecutive common factors, with each of them accounting for the maximum possible portion of the variance shared amongst the observable variables, which corresponds to the V_k variable, as shown in equation [7-39]. The mathematical solution to this process involves applying Lagrange Multipliers to an eigenvalue and eigenvector extraction method. The full procedure of this approach can be consulted in (370; 384).

On the other hand, the Minimum Residuals technique is based on obtaining a pattern factor matrix A_{vxq} which represents with the highest fidelity that is possible the correlations amongst the original variables. This is done by minimising the squared differences between the non-diagonal terms of the original correlation matrix and the reproduced correlations matrix R_{vzv} , which corresponds to the product of the factor pattern matrix with its transpose, as seen in equation [7-34]. Mathematically, this approach is represented by the following expression:

$$\min || [R_{vzv} - I_{vzv}] - [A_{vxq}A'_{qxv} - \text{diag}(A_{vxq}A'_{qxv})] || \quad [7-43]$$

The optimisation process represented by the previous equation seeks to estimate the terms of the pattern factor matrix. To achieve this, it is necessary to set in advance the number of common factors q to be extracted, and a starting value is also needed for the different terms of the A_{vxq} matrix. In order to solve these issues, it is possible to employ the solution obtained from the principal factor method as a starting point for the

optimisation process. A final point of consideration for this method is the necessity to impose v nonlinear restrictions for the communality of each variable so that its value does not surpass the unity. The form of these restrictions would be that of a q -dimension hyper ellipsoid, as demonstrated in (385).

With respect to the strenghts of each of the aforementioned factor extractions techniques, the main contribution of the Principal Factor technique is that it allows a certain degree of flexibility when selecting the number of factors to be extracted, and it also serves as an initial point for the optimisation process required in the Minimum Residuals method. In turn, this latter approach has been noted to perform better than other factor extraction strategies in scenarios with low sample sizes (371), which is the case of the analyses to be conducted within this chapter. Furthermore, it has also been highlighted that the Minimum Residuals approach also performs better in recovering factors which account for relatively low portions of variance (372), so it has a higher probability of capturing latent trends which may represent subtler design tendencies of the RPA of study.

Since the Minimum Residuals method requires the estimation of the number of common factors q from the Principal Factor method, this latter approach must be used in the first place. Therefore, it is necessary to expound on the criteria for the selection of the number of factors to be retained from this technique. There are numerous approaches to this issue (371; 377), with the most appropriate one depending on the characteristics of the problem of study. One of the most common methods is known as the Scree Test, and it is presented in (386) and further developed within reference (387), where its full significance and application process are detailed. This approach consists in analysing the differences amongst the scores of the eigenvalues corresponding to the different common factors. These eigenvalues are associated with the portion of common variance accounted for each factor. As each factor which is sequentially extracted has a lower portion of remaining variance, at certain point the variance which is accounted for by the factors which are extracted later on is lower. Therefore, it is sought to identify the factors in which the highest decrements in the eigenvalues appear, which will aid to select the last factor to be retained. This analysis is typically undertaken by plotting the eigenvalue scores in decreasing order so as to identify the last significant common factor.

In this research, an additional methodology is proposed for selecting the number of factors that shall be extracted. This procedure does not only seek to be more quantitative and repeatable than the scree test, but it will also take into account aspects related to the usual acceptable errors accounted for in the conceptual design stage, so as to ensure an adequate accuracy from the viewpoint of aircraft conceptual design. Considering the range of acceptable error of around 10-20 % as stated in previous works, common factors shall be retained until more than 90 % of the common variance amongst the observed variables of study is accounted for. Consequently, the remaining variance which is not accounted for within the common factors would fall within the acceptable error interval in conceptual design. Leaving a portion of variance below 10 % to the specific factors shall

be key, since it will only be possible to estimate the common ones in the design process that shall be derived from the factor analysis approach later on this chapter. Thereby, if the specific factors accounted for a large portion of the total variance, the estimation of the observable variables from the common factors would be affected by a larger uncertainty.

An additional consideration will be taken into account with respect to the statistical significance of the factors to be retained. The loadings of the A_{vxq} factor pattern matrix represent the linear correlation coefficients between the observable variable that corresponds to the row of the matrix which is being considered, and the common factor associated with the column (370). Thereby, establishing an analogy with the regression model laid out in the previous subsection, an hypothesis test can be conducted in order to verify whether the retained factors are statistically significant in the determination of the observable variables, and thus if they represent noteworthy design tendencies for the database RPA. Therefore, when conducting the factor extraction process, the statistical significance of the coefficients of each factor shall be assessed, and if it is seen that certain factors do not yield adequate results when performing the hypothesis test, they shall be discarded. Typically, this will coincide with those factors which do not account for a large portion of variance of the observable variables.

Therefore, as a summary, the new method for factor extraction proposed in this chapter is based on the following two aspects:

- 1) That the ensemble of all the retained factors account for more than 90 % of the total variance of the observed variables. This seeks to limit the variance which is left for the specific factors, as it will not be possible to estimate for the new aircraft to be designed through the factor analysis-based approach.
- 2) That each factor shows a statistically significant correlation with the observed variables, which represent the values that will be involved in the RPA design process. If the factor presents a weak correlation with the observed variables, it will be discarded.

In any case, the results obtained from this approach shall be compared with those obtained from the classic Scree Test method, which will also serve to validate the new methodology.

(g) Interpretation of common factors

Once the number of common factors to be retained has been established, and these common factors have been extracted, the following step would be to evaluate the interpretation of the factor through its relationship with the observable variables. These relationships are key, as they reflect the design trends unveiled by these latent factors. Some of the proposed advice regarding the interpretation of factors can be consulted in (370; 377).

Overall, it is advisable to examine the magnitude of the factor loadings, which as mentioned beforehand correspond to the coefficients of correlation between each factor-variable pair, so as to aid in the interpretation of the factor meanings. It should be noted that the process of evaluating the statistical significance of the factor loadings which was proposed in the previous step is also useful in this matter. If the statistical tests for a certain factor-variable loading yield good results, the relationship between the factor and the variable can be substantiated from the viewpoint of the population, thus strengthening the link between the factor with the particular variable associated to the loading.

(h) Common factor estimation

Once the values of the A_{vxq} array have been obtained through the factor extraction procedures mentioned beforehand, the loadings corresponding to the specific factors contained in the D_{vxx} array can be calculated through the use of equation [7-36]. Once these two matrices have been obtained, the last step in the factor analytic procedure would be to estimate the values of the common factors f_k for each of the RPA of the database. This would quantify the magnitude in which each aircraft partakes in the design tendencies interpreted from the results obtained in the common factor analysis. This allows to characterise the different aircraft according to these new variables in parallel to the way in which the RPA are usually defined by the values of the observable variables that have been considered (b, S_w, S_h, S_v). In the open literature, the most common method to estimate these values is to hypothesise that the common factors are defined by a multiple regression obtained from the observable variables. Once again, the link between the factor analysis approach with that of multiple regression is seen at this step. This procedure is considered to be less prone to error by some of the authors of this discipline (388). The equation that describes this regression would be the following:

$$\hat{F}_{nxq} = Z_{nxv}\beta_{vxq} \quad [7-44]$$

where:

- $\hat{F}_{nxq}$ is the matrix of the estimated values of the common factors. It contains in each row the values of the q factors for each of the n aircraft.
- Z_{nxv} is the data matrix obtained from the RPA database, with aircraft sorted by rows and variables by columns.
- β_{vxq} represents the multiple linear regression coefficients.

The β_{vxq} coefficients can be obtained from the following equation:

$$\beta_{vxq} = R_{vxx}^{-1}A_{vxq} \quad [7-45]$$

Thus, the values of the common factors can be estimated for each of the RPA. In previous factor analytic studies, the magnitude of these factors along with their correlation with

the observable variables have been employed in order to establish certain “marker variables” amongst the observable ones so as to describe the problem of study with a fewer number of elements (388).

(i) Application to RPA conceptual design

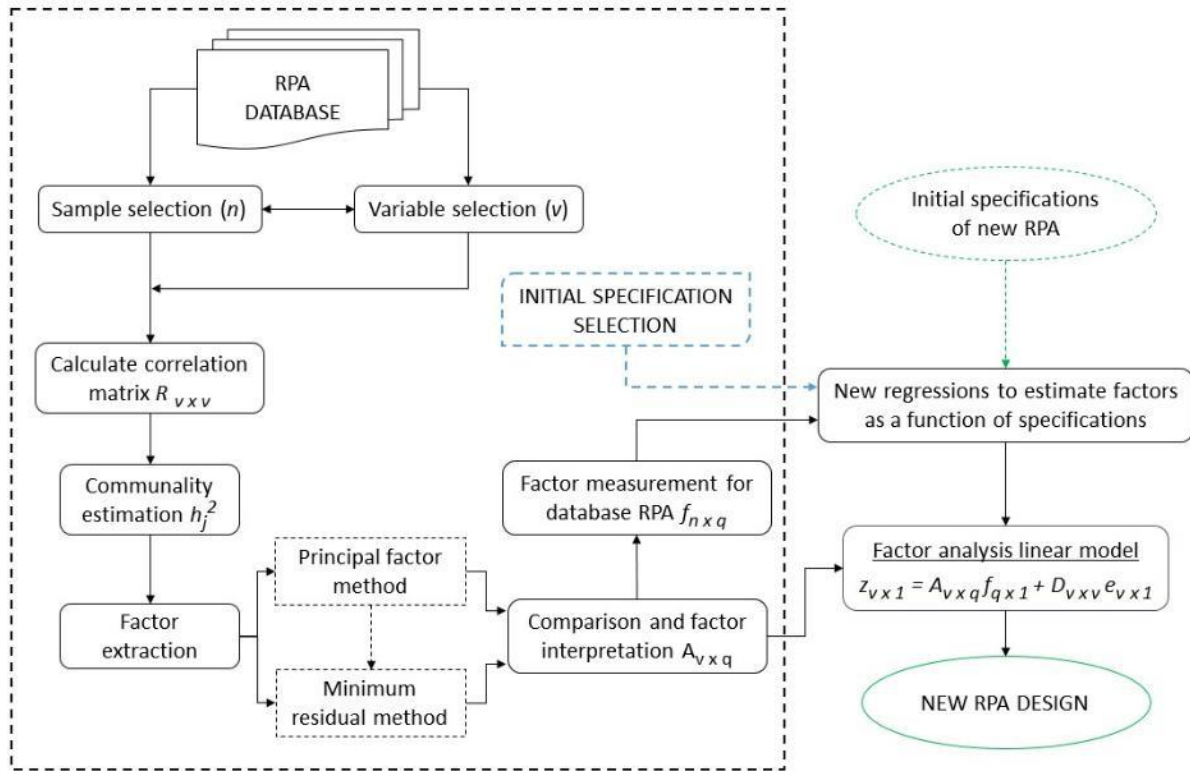


Figure 7-6. Factor analysis application roadmap to the RPA database. The results obtained shall be employed and tested for the sizing of new RPA not included in this database.

In the case of the present investigation, the objective is to employ the results obtained from the factor analytic procedure in the conceptual sizing of new RPA. Therefore, the approach proposed in this research is to establish, in view of the factor measurement results, new correlations between certain observable variables (selected among those included in the model which can also fit as starting values of the geometric sizing procedure) and the unobservable common factors. This procedure can be conducted at this step since the values of the observable variables are known for the aircraft within the database, and the quantification of the common factors was already obtained in the previous step of factor measurement. Therefore, at this point, the common factor can be considered one more variable among those which describe each RPA of the database, along with the observable ones such as $MTOM$, S_w , b_w , since after the factor measurement step, the numeric value of the common factor has been estimated for each aircraft. Thereby, it is feasible to establish the aforementioned correlations for the RPA contained in the database.

Then, these correlations between the factors and the observable variables which can be considered as starting points of a geometric sizing process shall be applied to the task of designing a new RPA. It can be assumed that the variables which have been selected as the starting values of the design workflow are known, so the regressions previously estimated for the RPA in the database can be employed to obtain the values of the underlying common factors for the new RPA. Then, employing the linear model of equation [7-33], the values of the other observable variables can be obtained from the common factor. To do this, there is a final hypothesis which must be considered, which is that the specific factor for each variable for the new RPA can be discarded when estimating the other observable variables from the common factors. This will be feasible if the proportion of variance accounted for by the specific factors is very low when compared to that of the common ones, which is one of the main points highlighted during the development above when choosing the factor extraction strategy.

It should be stated that since the factor analysis methodology analyses the covariances among all variables simultaneously, and the underlying factors are extracted on the basis of these multivariate interactions, it is not feasible to readily predict from the initial data matrix which observable variables are going to show stronger correlations with the common factors. At the factor measurement step, this means that it is cannot be predicted in advance which variables can be used as predictors to establish new regressions that can estimate the common factors. Thereby, even if observable variables which represent potential starting points of the design process have been included in the model, it might not be possible to use then in the factor estimation. It is required to study this issue in each particular case, thus further details shall be given in section 7.7, where the factor analysis methodology shall be applied to the RPA database that will be introduced in subsection 7.4.3. The roadmap illustrating the procedure which will be followed in the application of factor analysis for RPA design is illustrated in Figure 7-6.

7.4.3. RPA database

In this section, the matters concerning the RPA database which has been gathered as part of the work on this thesis shall be expounded. This database constitutes a fundamental asset towards obtaining the statistical results which will be commented in sections 7.6 and 7.7. The reasons driving the need to compile a database for this research were outlined in 7.2. As a summary, there are two main ground for this:

- 1) Albeit previous works have already compiled RPA databases, these have been developed in-house by the authors in all cases, so access to these data sources is not available.
- 2) The work developed in this chapter places special emphasis on a particular set of variables, namely those of the tail surfaces, fuselage, and tail booms, which have been seldom covered by previous works. Furthermore, a classification attending

to general layout shall be emphasised. Therefore, even if the previous databases were available, most do not include these aspects.

(a) Data gathering process and database construction

Regarding the sources from which data has been gathered in order to compile the database, the primary reference has been the ensemble of two different editions of the Jane's Yearbook on Unmanned Aircraft (37; 389) as well as the Web Database (390), which constitutes one of the most extensive sources of information for RPAS. Another source of information spanning many different RPAS which has been consulted in the compilation process is the book "RPAS A Global Perspective" (32). Additionally, the book of (391) also contains information on various RPAS employed in the Naval Research Laboratory (NRL) of the USA.

Furthermore, additional information has been collected from different sources found on the Web, mainly from manufacturer's brochure. In this case, the depth of the information provided in each case can present significant variations. The search has been conducted firstly by employing a series of keywords which include, amongst others: 'RPA', 'RPAS', 'UAV', 'UAS', 'drone', 'remote aircraft', 'unmanned aircraft', etc. This methodology has not only been applied in established search engines, but also within the websites of the manufacturers themselves. Some of the resources which have been found include technical brochures, databases, and newsletters, sorted in descending order of information reliability. Once the different manufacturers have been identified, a more in-depth search within their websites was also conducted so as to complete and contrast the compiled information. Finally, as it will be commented later on, most of the aforementioned sources did not contain thorough data of the main parameters of the aerodynamic surfaces, so these have had to be measured in three-view drawings of the highest quality possible, which were also mainly found on the Web.

With this, the resulting database has compiled data on 406 fixed-wing RPA. Further along this subsection, some preliminary results representing the overall content of the database shall be given.

(b) Categorical classifications used in the database

As introduced beforehand through this chapter, the use of classifications to group different aircraft (in this case RPA) attending to diverse criteria is one of the most essential steps when conducting statistical analyses within this field. These categorisations allow to assemble sets of RPA which present similar characteristics, thereby greatly reducing the scatter when statistical trends are obtained for each group. Their advantages have been highlighted in previous works within this field (39; 40; 46), where the authors usually supported the use of category-specific results above the general ones obtained from the whole database. This is not only seen in RPA design, as previous works in the broad realm of applications of factor analysis have also supported this perspective (373; 383). Usually, the criteria to categorise the aircraft continued within

the database is related to certain qualitative aspects, such as powerplant type, or NATO category; albeit in some cases some of these groupings are determined themselves through quantitative aspects, such as the case of the latter one.

As it can be seen, the choice of the classifications to be employed within this research shall have a decisive impact on the results obtained from the statistical analyses to be employed later on. Section 7.2 has already covered some of the categories used in previous works, with most of them yielding significant differences in the estimated trends to those obtained with the overall database. From the various classifications, perhaps the one which has been seen to have a greatest impact on the results derived from the statistical analysis is the one attending to powerplant type, which is one of the main highlights of the works of (36; 39). This could be expected, as this kind of categorisation has also had a significant impact in the field of manned aeroplane statistical approaches. Other authors within the framework of RPAS propose different classifications, with some being according to mission, operational altitude, weight, or diverse combinations of these criteria (1; 5; 6; 13; 20; 26). However, most of these research efforts are not extensively focused on obtaining statistical regressions for variables related to the design of these aircraft. Furthermore, as already noted in section 1.2, the classifications attending to performance and mission aspects tend to have relatively blurry and changing frontiers among their categories, complicating their use in works such as the one developed here.

In contrast, other classification criteria, such as the consideration of the overall aerodynamic layout, have seldom been taken into account in previous investigations. However, in view of the reasons expounded in 7.1 and 7.2, this separation attending to the RPA configuration shall be one of the highlights of this work. It does not only cover a current gap in statistical analysis within this field, but its selection is also tightly related to some of the variables of main interest in this line of research, due to the emphasis on the sizing of the diverse aerodynamic surfaces including those of the tail unit. This kind of classification has already been employed in the work of (38), yielding good results. Furthermore, in previous research on manned aircraft design, the separation of data attending to tail type has also often resulting in significant differences in the correlations obtained for each of the configurations (42; 392). Therefore, this categorisation shall be the main one to be employed through the statistical analyses to be conducted on the database, and it shall group different RPA attending to the type and relative position of their aerodynamic surfaces, taking into account their overall layout. At some points, a classification attending to the union of the tail surfaces with the main airframe will also be considered, since it will be seen that it presents significant couplings with the overall layout. Furthermore, it is also related to the type and position of the tail surfaces, thus linking once again with one of the main areas of effort of the line of work presented here.

It is also relevant to consider how many simultaneous classifications shall be employed. For instance, a separation of the aircraft contained in the database attending to both their general configuration as well as to their powerplant type could be considered. This can be

expected to further reduce the scatter of the regressions, since the groups which are formed are even more homogeneous. Furthermore, the powerplant classification has yielded significant differences in the extracted trends within previous works. However, this exercise of adding more groupings should be made with caution. The reason for this is that, while the scatter may be reduced, the sample size of each group is further diminished. As it was seen through the previous theoretical background on both the regression and factor analysis approaches, reduced sample sizes have a negative effect on statistical significance, and thus on potential inference capabilities. This will reduce the values of the t-statistics and F-statistics which were seen for instance in equations [7-27] and [7-31], which would require much higher values of the coefficients of correlation to compensate the reduced sample size and support the statistical significance of the results. Therefore, there may come a point where the increase in regression fit metrics is not worth the worse results obtained in the hypotheses tests. This is coupled to the issues related to data scarcity within the realm of RPAS, which will be commented in the following section.

Considering all of the above, the two main classifications employed in the statistical analyses to be expounded through this chapter shall be the ones based on general layout and on powerplant type. Furthermore, as commented beforehand, the type of tail union with the main airframe will also be considered at certain points. The categories which have been defined for each of these classifications have been summarised in Table 7-2.

(c) Overview of general database trends

In a similar vein to previous works performing studies on manned aeroplane and RPA databases, an overview of the main results and contents of the database is provided here. Some overall descriptive figures will be shown on the RPA included within the dataset. Considering that the sample size of the database is relatively sizeable, these general trends also serve to present an image of the current landscape of fixed-wing RPA designs. Furthermore, these results shall serve to contextualise the ones given later on along this chapter, which will have a more specific nature, being focused in particular aspects.

Table 7-2. Summary of the main classification criteria and categories considered in this research.

Configuration classification	Powerplant classification	Tail union classification
• Conventional tail • T-tail • V-tail • Y-tail • H-tail • Wing and VTP • Tailless • Other arrangements	• Reciprocating engine • Electric powerplant • Turbine engine • Other powerplants • No powerplant	• Conventional union • Single tail boom • Double tail boom • Tailless • Other unions

Firstly, the main results from the database according to the three main classifications introduced in the previous sections shall be presented. The trends by aerodynamic layout as well as by the type of tail union with airframe are shown in Figure 7-7.

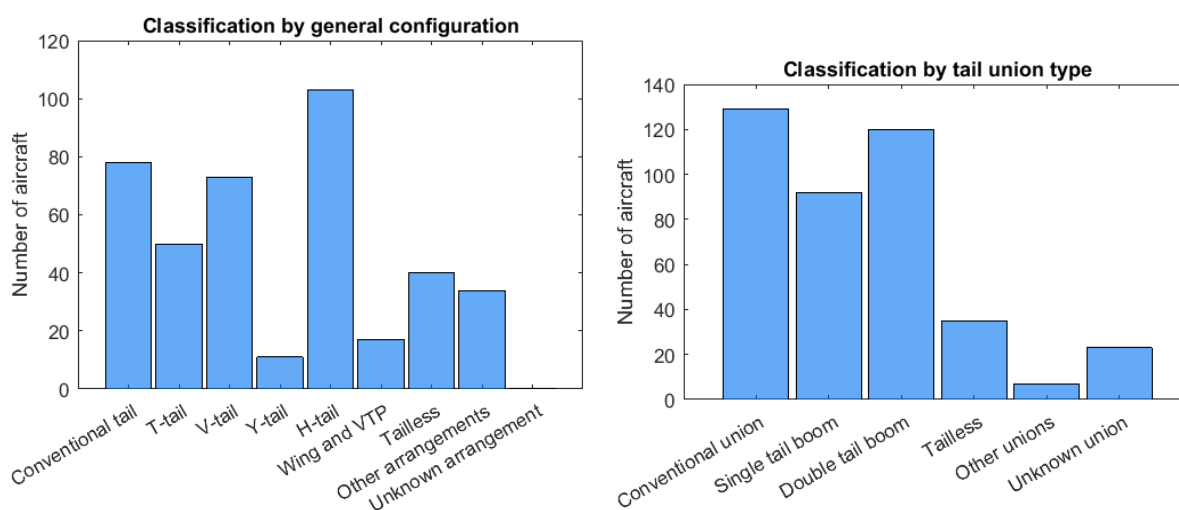


Figure 7-7. Histograms quantifying the number of aircraft in the database according to the general configuration and tail union with airframe classifications.

The study of the general configuration trends reveals that the most sizeable layouts are the H-tail, conventional tail, V-tail, and T-tail. These findings are compatible with remarks from previous authors in the field, who have highlighted that the H-tail configuration is the most extended one for these aircraft (53). This is a configuration which is usually considered unconventional within the realm of manned aircraft, as it is the case of the V-tail layout which also contains a remarkably large number of RPA, even surpassing the T-tail, with this configuration being much more extended in manned aircraft. These differences in the most usual layouts of RPA when compared to conventionally-piloted aeroplanes further strengthens the need of developing new design methods for RPA, as their usual design space shows significant differences. In contrast to the aforementioned configurations, the tailless layout, which includes BWB-type RPA, is comparatively less extended. This was already highlighted in previous studies, where a comparative lack of available designs with this configuration was noted, hindering the statistical analysis of these configurations (122).

Moving on to the type of tail union, the category with the largest number of aircraft is that of conventional union, which corresponds to the tail unit being directly connected to the fuselage, usually in its rear-end. However, if the two tail boom groups are added together, they nearly double the number of RPA within the aforementioned conventional union type, highlighting the remarkable number of unmanned aircraft with this kind of feature, which also fits previous findings within the state-of-the-art (53).

Albeit one of the main contributions of this work shall be to leverage the results of employing the classifications of aerodynamic layout and of tail union, which as it will be

seen, yield significant differences in some of the correlations, the powerplant categorisation has proven its usefulness in previous works. Therefore, Figure 7-8 showcases the results from this classification. The relative number of RPA pertaining to each category with respect to the overall of the database remains consistent with those of previous works (36; 39), aiding to validate the data gathering process and database representativity. It is highlighted that reciprocating engine RPA are the most common by a certain margin, which is also seen in the aforementioned previous works. The second most sizeable group is that of electric RPA, and this is then followed by the rest of the categories, which are comparatively minority. These results highlight that, in case of keeping a single powerplant type for conducting the correlations, the group of reciprocating engine RPA would seem to be the most suitable.

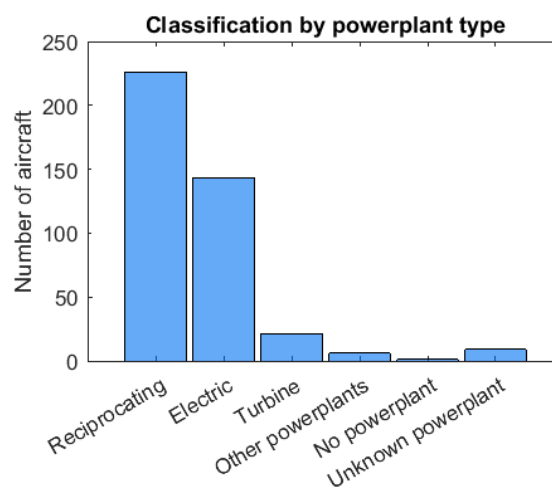


Figure 7-8. Number of RPA in the aircraft as classified by powerplant type.

However, it should also be highlighted that there can be relevant interactions among the aforementioned categories, and also when considering the groups alongside certain continuous variables. These types of trends have seldom been quantified in previous works, so some of them would constitute a novel contribution of the analyses presented in this thesis. For instance, it seems reasonable that the use of electric RPA is mostly focused on very small aircraft, whereas the reciprocating engine category could be more scattered through an expansive range of *MTOM*. This has been analysed in Figure 7-9.

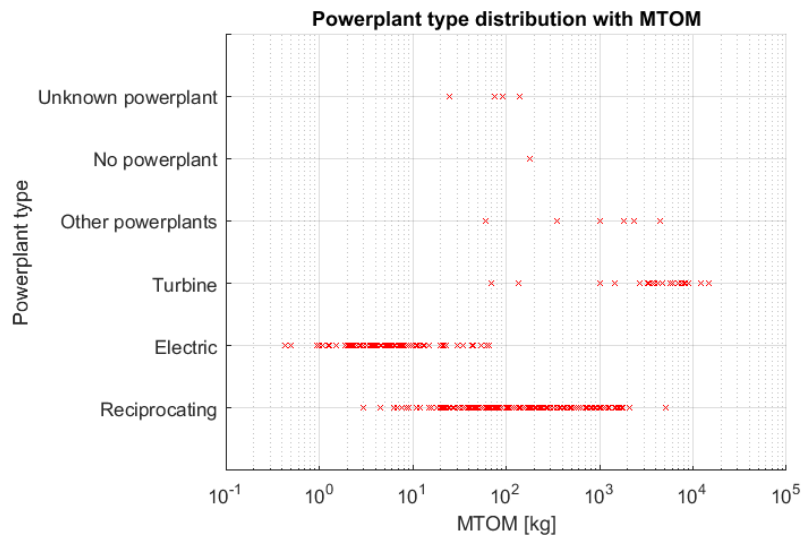


Figure 7-9. Use of different powerplant types along the continuum of MTOM values for the full database.

Here, it is seen that the expected trend is verified. These results are similar to those obtained through a similar representation as seen in the work of (36). Overall, it is seen that the reciprocating engine type would be the foremost category to consider within this work, as it does not only present the largest number of RPA, but it also spans the largest range of mass values. As commented beforehand in 2.1, the applicability of a design methodology is a relevant characteristic to consider so as to ensure that it can be used through the largest range that it is possible. Choosing the reciprocating category allows for RPA from tens of kilograms up to thousands to fall within the scope of the design methods which can be developed when focusing on this group. In contrast, the electric and turbine powerplant categories have a narrower range, thus design methods developed for these aircraft would only be usable within their corresponding ranges of *MTOM*.

Another interaction analysis which is relevant to the main categories considered within this line of research would be to study if there are couplings among the general configuration and the tail union type. This assessment is shown in Figure 7-10. As it can be seen, the case of the H-tail is remarkable, since this layout is nearly always used alongside a double tail boom union, showing a strong coupling between these two categories. With respect to conventional and T-tail configurations, these are used both alongside direct tail unions and also single tail boom ones, but in these cases double tail boom unions would not be present. The configuration which shows a largest variety of tail union types is the V-tail, as it is shown to be used both alongside direct unions as well as with single tail booms and double tail booms. However, it should be noted that the latter two union types seem to be more prevalent in lower ranges of MTOM, whereas this scenario is inverted for larger aircraft. These considerations shall be relevant in further sections of this chapter when selecting the categories to be employed in various statistical analyses and also when interpreting the trends that will be obtained from them. In this

case, no similar analyses were found in the open literature, thus these insights would be among the novel results of this thesis.

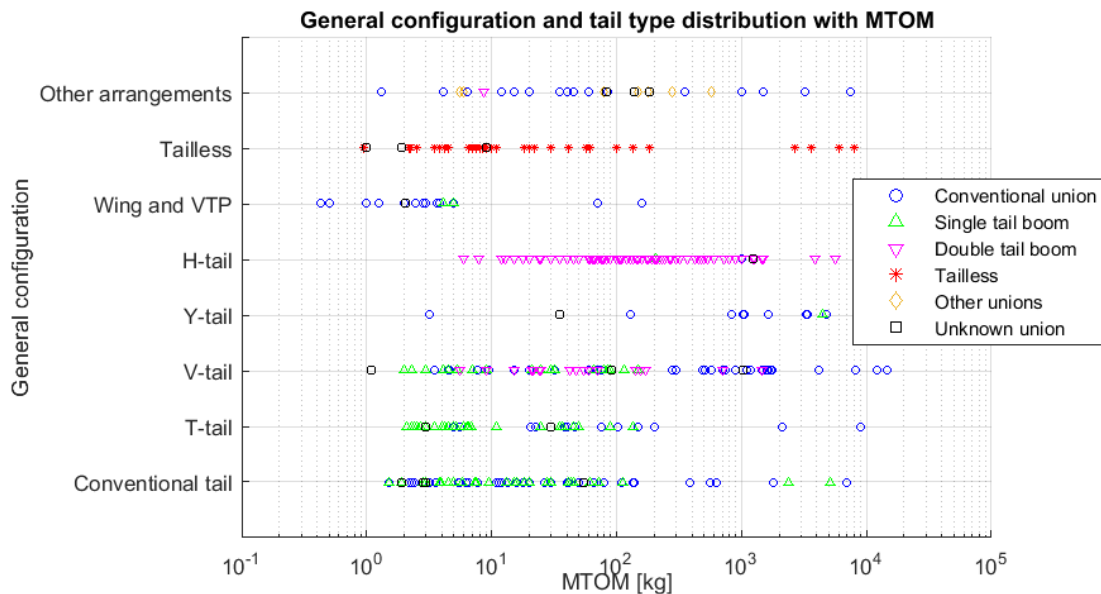


Figure 7-10. Analysis of interactions among general configuration, tail union type, and MTOM.

At this point, some further comments can be made with respect to the mismatch between the most usual layouts in RPA and the capabilities of computerised design environments in this regard. As it was already brought forward in advance within 4.6.2, even in the realm of RPA, the V-tail and H-tail layouts were only considered in a few design packages. In contrast, the tailless layout was much more extended among these suites when compared to other configurations. At this point, and in view of the new results presented here on the current design trends of RPA, it can be seen that a higher attention to the V-tail and H-tail layouts would potentially enhancing the capabilities of design environments in relation to RPA development. This would fit within the second point of future work towards design packages for RPA, with the new methods to be proposed within the current chapter seeking to also aid in this regard, as obtaining statistical trends for the most usual types of layouts in RPA is emphasised here.

Another interaction analysis which is studied here considers the interrelationships among wing planform type, general configuration, and MTOM. As it will be seen later on when proposing the design workflow corresponding to section 7.6, at a certain point in the process, the designer will have to make a decision on the wing planform type, which shall have an influence on other wing characteristics. The results presented here in this regard can aid in deciding this categorical selection at that point in time, in view of the type of configuration which has been selected for the aircraft and its MTOM value, which shall be known aspects when arriving at that step of the workflow. The results are shown in Figure 7-11. It is noted that the wing planform classification used here is according to the one proposed by Gudmundsson (9).

In view of the figure, it is seen that there are also some interactions worth highlighting here. The wing types which are used more extensively and through a wider range of *MTOM* values are the straight-tapered and semi-tapered ones. Rectangular wings are very common up until the tactical range of *MTOM*, but as the size and weight of the aircraft increase beyond that point, they are then seen less commonly. Elliptical wings are mostly employed in small and small tactical RPA, and overall they are relatively scarce when compared to the aforementioned kinds. Other planforms such as the delta wing or the crescent wing are seldom employed, and they usually appear alongside unconventional arrangements.

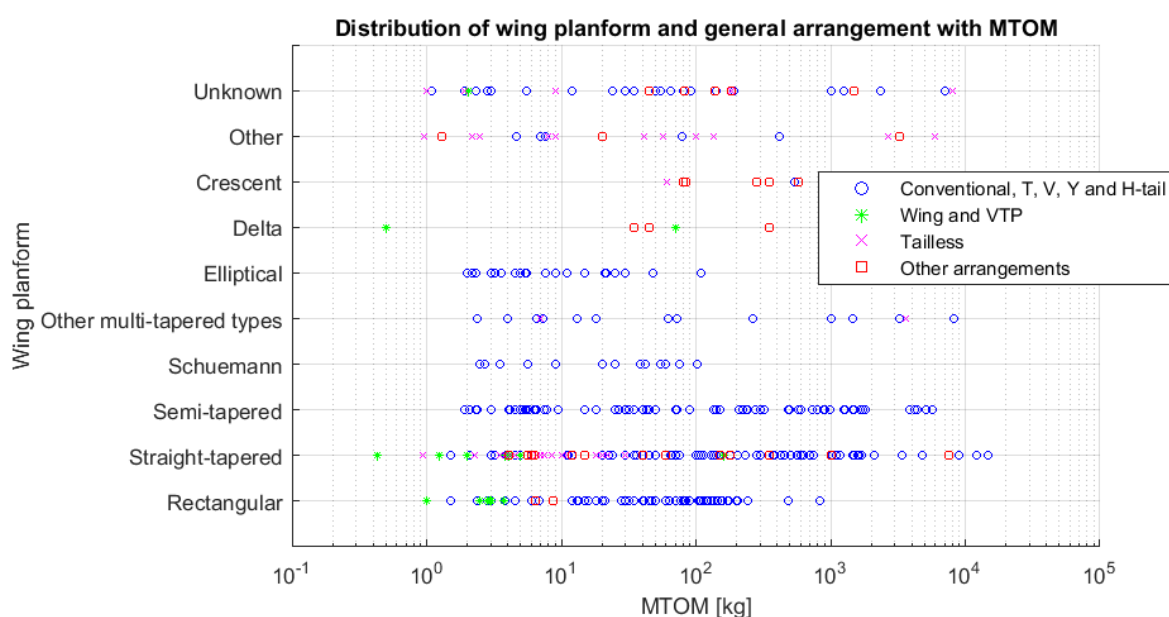


Figure 7-11. Analysis of interactions among wing planform type, general configuration, and *MTOM*.

Finally, another combination of categorical and continuous variable interaction is studied in Figure 7-12. This case analyses along the *MTOM* continuum the prevalence of different propeller types attending to whether they have fixed or variable pitch. A key aspect seen here with respect to the previous graphs is that the information on this variable is unknown for the majority of RPA compiled in the database. This is an example of a more expansive issue that will be discussed further below, which relates to the overall lack of data on certain RPA variables. Aside from this aspect, it is seen that fixed pitch propellers are the most common ones, as they can be seen from small RPA up to those well into the tactical range, even appearing in some vehicles close to the MALE category. In contrast, variable pitch propellers tend to appear from the MALE unmanned aircraft onward.

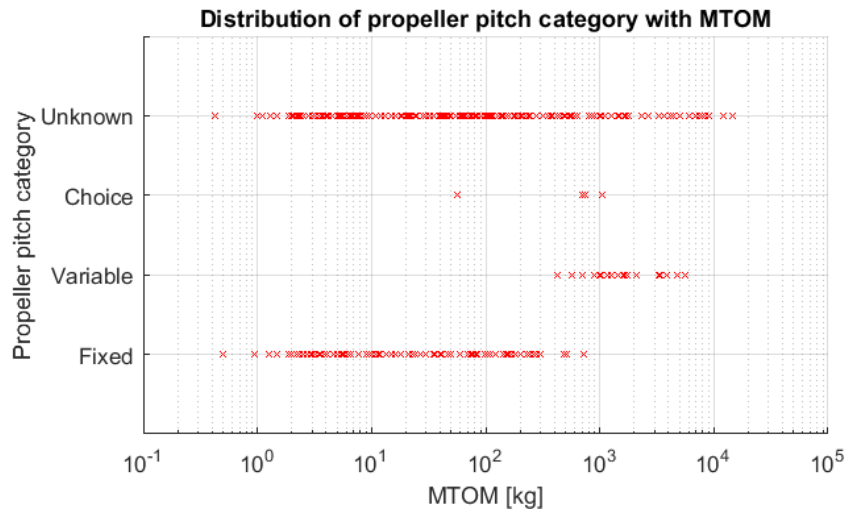


Figure 7-12. Use of different propeller pitch types along the continuum of MTOM values for the full database.

Before moving on to the most outstanding variables compiled in the database, it is relevant to highlight the number of three-view drawings of RPA which were found during the dataset compilation. As mentioned beforehand, and as it will be seen with more detail, many references only contain information about general variables of the RPA included within them. However, other parameters, such as the surface areas of HTP and VTP, are very seldom found in the open literature. This is the reason why it was necessary to measure these values from three-view drawings using as a reference other overall dimensions of the RPA which were already known, such as the wingspan or the general length. However, even finding these three-view drawings constitutes a complex prospect, as it has only been possible to gather a total of 64 RPA, which only amounts for fewer than 16 % of the RPA included in the database. This results in remarkable limitations in the available data which have a direct effect on the dataset, and thus on the results of the statistical methods which will be applied later on in this chapter.

As mentioned beforehand, the design methodologies to be developed within this chapter emphasise some variables which were not studied in detail within previous works. Taking into consideration that from the state-of-the-art analysis, it was sought to obtain trends for tail unit, fuselage, and tail boom variables, these have not only been included in the database, but particular effort has been put into finding or measuring their values for the RPA compiled in the database. Table 7-3 contains information on some of the most relevant variables that were considered when building the database, along with the percentage of aircraft for which they were found.

Table 7-3. Example variables of the database which have an influence in later statistical analyses, along with the percentage of aircraft of the database for which the variable's value is known. "Data" indicates that the value is found directly as numerical information within the data sources consulted to compile the database. "Measured" designates those cases where measurements on three-view drawings were obtained to complement the scarce volume of data directly found on the references.

Name	Symbol	Percent	Name	Symbol	Percent
Maximum Take-Off Mass	<i>MTOM</i>	98%	Wing area (data)	<i>S_w</i>	20%
Operating Empty Mass	<i>OEM</i>	43%	Wing area (data + measured)	<i>S_w</i>	25%
Payload ^a	<i>PL</i>	84%	HTP surface area (data)	<i>S_h</i>	<1%
Wingspan	<i>b</i>	98%	HTP surface area (data + measured)	<i>S_h</i>	11%
Length	<i>l</i>	87%	Power	<i>P</i>	47%
Fuselage length (data)	<i>l_f</i>	7%	Cruise speed ^b	<i>V_c</i>	89%
Fuselage length (data + measured)	<i>l_f</i>	20%	Endurance ^a	<i>E</i>	94%

a: In the RPA operation, payload and endurance values are mission-dependent. However, most data found in the sources consulted for the database compilation only state these values under entries labelled "payload" and "endurance", with very few cases providing a higher level of specificity to describe the mission and the payload-endurance combinations which may appear in practical operations. Therefore, the database has grouped all generic payload and endurance data under these variables as stated in the table, and it is considered that they signify representative values of such features in a typical operation. **b:** a similar scenario to that of *PL* and *E* is found for the RPA characteristic airspeeds. In some cases, the data sources only state a value for "speed". These have been included within this *V_c* variable in the database along with other generic data of cruising of flight speed. Data on other airspeeds that are provided with higher specificity, such as "loiter speed" or "maximum cruise speed" are rarer to find.

In view of this assessment on the volume of data found in the references which were consulted, it is seen that there is a remarkable hurdle regarding data scarcity in the field of RPA. However, this lack of data is not uniform, since it shows large variations among distinct variables. Those parameters that are related to overall characteristics, measures, and performance metrics of the aircraft are found very frequently within the data sources. However, when moving on to variables measuring some specific aspects of certain components such as the fuselage or the HTP, these values are almost never found. To put the best effort into filling these gaps, measuring in three-view drawings has been fundamental. However, considering that not many images of this kind were found, and in some cases, there were of relatively low quality, this does not yet allow to compile a comprehensive dataset with few gaps, which would be the best case scenario for conducting statistical analyses.

This challenge related to data compilation is not particular of this thesis, as it was already explicitly highlighted by previous authors (15; 18; 35; 61), some of whom even emphasised that the data availability and completeness is much higher in the realm of manned aeroplanes. Even in other works within the topical area of statistical approaches for RPA aside from those cited beforehand, a comparison between the volume of data

points used within each correlation also reveals remarkable differences in data volume depending on the variables involved. depending on the correlation that is calculated, a remarkably different number of data points is found. Therefore, it can be seen that these issues have also affected previous research efforts within this area. Further comments regarding this subject shall be given in the next section, which is focused on the set of challenges related to data scarcity within this field.

(d) Equivalent wing definition applied in the database

As it has been seen in Figure 7-11, albeit most of the RPA in the database have rectangular or straight-tapered wings, there are other designs with more complex wing planforms. This variability in wing geometry and in the parameters needed to describe each of them complicates tabulation within the database and also a direct comparison between different aircraft.

Therefore, an equivalent wing planform has been defined for each of the RPA of the database. This concept is based on that of Roskam (8), and its main basis consists in defining a straight-tapered equivalent wing with a single trapezoidal portion. This equivalent wing is defined in such a way that it has similar properties to the original one, so it has a series of geometric equivalences with the starting wing. In the case of this work, it has been chosen that the equivalent wing for RPA has equal surface area, wingspan, and Mean Aerodynamic Chord (MAC) to the original one. The reasons for selecting each of these variables are as follows:

- **Wing surface area ($S_w' = S_w$):** due to its relationship with the lift and drag characteristics of the wing, and other key parameters such as the AR.
- **Wingspan ($b_w' = b_w$):** due to being linked with the AR, so that along the previous characteristics it results in an equivalent wing of overall equal AR, as this is a key design parameter linked with many relevant aerodynamic and structural aspects.
- **MAC ($MAC_w' = MAC_w$):** since this parameter is also related to overall aerodynamic characteristics of the wing, and it also appears in the definition of longitudinal volume coefficients.

Considering the above, the root chord, tip chord, and taper ratio of the equivalent wing are obtained through the following expressions:

$$c_r' = \frac{2 + \sqrt{4 - 4 \frac{b_w}{S_w} \left(\frac{4S_w}{b_w} - 3MAC_w \right)}}{\frac{2b_w}{S_w}} \quad [7-46]$$

$$\lambda_w' = \frac{2S_w}{b_w c_r'} - 1 \quad [7-47]$$

$$c_t' = \lambda_w' c_r' \quad [7-48]$$

Since the various trends and correlations obtained from the database shall thus be related to equivalent wings, the resulting RPA would have a straight-tapered one in the first design approximation. However, the designer can then chose to produce a wing with a different planform which maintains the surface area, wingspan, and MAC of the equivalent wing, so as to define different wing planforms as required by the overall design decisions. In any case, it is noted that in the conceptual design stage, the definition of a straight-tapered wing which can then be evolved into more complex shapes is a usual practice which is also seen in recent research (41).

7.5. Challenges in RPA statistical analysis

Through the previous sections, various hurdles have been seen towards the development of new statistical approaches for RPA design. In spite of there being a comparatively large number of works within this topical area when compared to other ones in the field of conceptual design, it can be argued that various issues are still present that complicate the extraction of new statistical trends and also the possibility of obtaining more meaningful results. Some of these challenges have already been found during the database compilation process done in this thesis, and it is expected that they will also affect the statistical results to be obtained from this dataset. Furthermore, at the analysis stage, some additional issues might appear. Therefore, before moving forward to the application of the statistical methodologies, an overview is provided here of some of the aspects mentioned beforehand, as well as some additional considerations to take into account during the statistical experimentation that follows.

From the issues with RPA statistical design that have been commented beforehand, it can be seen that many of these aspects are tightly interrelated and influence one another. The main essential challenges that have been seen could be summarised in the following points:

- 1) **High variability of RPA designs, resulting in a significant scatter:** this diversity of designs was already commented in chapter 1. The fact that many existing RPA have been designed through trial-and-error approach instead of through methodological guidelines (21) might be one of the reasons explaining the remarkable scatter of data points seen in this field. This complicates categorisation, since it may be more difficult to detect homogeneous groups of similar designs, and it also impacts the goodness of fit of the statistical results. It has been seen through the formulae presented in 7.4.1 and 7.4.2 that a high scatter penalises the statistical significance and also the main regression metrics, such as the R^2 .
- 2) **Diverse categorisations:** this point is tightly linked with the previous one, as the design variety of RPAS gives rise to many different possible schemas that can be used to group these aircraft. These classifications may be leveraged as a way to

reduce scatter, even employing more than one type to mitigate distinct sources of variation (for instance, those pertaining to the powerplant, and the ones related to the type of tail, which correspond to different classifications). This can be particularly relevant when considering the proven differences between the trends of distinct RPA categories, for instance as observed in previous works with respect to the one on powerplant type (36; 39). However, if various different classification schemas are employed at the same time, each of the resulting aircraft groups shall contain a much lower number of aircraft. A reduced sample size has a negative impact on statistical significance, as seen through 7.4.1 when dealing with the hypotheses tests, which would require the scatter reduction to compensate the lower sample size, and this may not always happen, particularly when already managing very low number of individuals in the data matrices.

- 3) **Overall low volume of data in the literature:** as highlighted by previous authors (15; 35; 61), considering that the surge in RPAS design activities is relatively recent, the field is not as mature as that of manned aeroplanes, and the volume of available historical data is low. In spite of this, and in view of previous works as presented in 7.2, some authors have developed databases with a sizeable sample size, albeit as it is seen in the following point, in many cases the trends are manily focused on a few overall features of the RPA for which data is more readily found.
- 4) **Uneven distribution of the avilable data:** certain specific variables are seldom found in the different data sources, whereas general characteristics of the aircraft are much more abundant. This may explain why previous works have mostly focused on overall aircraft features such as MTOM, payload, wingspan, length, and endurance, with trends pertaining to other variables being much more difficult to find. It can be argued that this might also be one of the reasons for certain variable such as those of the tail surfaces having been mostly neglected until now within this field in comparison manned aircraft, where they have been studied much more frequently.
- 5) **Low number of three-view drawings:** the avilability of high-quality three view images could aid to surmount some of the data scarcity challenges mentioned above, as measures can be made directly on them. It has been seen that this approach has effectively caused a remarkable increase in the available data of certain variables within the research presented in this chapter, as quantified in Table 7-3. However, overall the number of available three-view drawings is low, thus data scarcity can only be mitigated up to a certain point.

As mentioned beforehand through the text, these hurdles present challenging interconnections. For instance, it was required to use two distinct classification schemas simultaneously to reduce scatter, but the quantity of data available were high, then the reduction in the sample size caused by the classification could be mitigated through the compilation of a larger volume of data. However, in the context of design data for RPA,

this is not the case, as there is not only an overall scarcity of information, but this shortage is even more pronounced for certain variables. This necessitates measuring these features in three view drawings, but once again, there is not an abundant amount of these images available in the open literature.

One of the most complex scenarios arising from these issues is the predicament between the need to ensure a good fit of the statistical model, and on the other hand, the requirement to support hypothesis testing related to inference capabilities. The first dimension can be assisted by the use of categorisations, since sources of variability are controlled by grouping the aircraft into more homogeneous ensembles. However, this reduces the sample size of each category, so unless the increase in model fit is very high, the second dimension may be penalised.

Furthermore, when taking into account the difficulty of finding information for specific variables such as the tail surface dimensions or the fuselage, another issue arises. Adding these characteristics could be advantageous since trends can be derived for aspects which were seldom covered in previous works, but in contrast, their particularly low data volume could affect the inference characteristics of the overall model. This is mainly due to the statistical methodologies expounded in 7.4 requiring complete data matrices to perform their calculations. The practical effect of this is that, if one of the individuals (in this case, an RPA), is missing a value for a single variable within the data matrix, then the full individual must be discarded from the set of analysis. Thereby, if the designer wishes to hold a larger number of variables in the study, there is a higher probability for each individual to present a single missing data value for the full amount of variables. Therefore, as the number of variables is increased, this can result in a concurrent decrease on the sample size when managing datasets or fields of research with an abundance of missing values, which is the case of the field of RPA design.

The fact that an increase in the number of variables of the model can be accompanied by a reduction of the sample size through the mechanism commented above constitutes another noteworthy issue. As seen in 7.4.1, the difference between n and p appears in various mathematical expressions, particularly those related to the hypothesis test of the multiple correlation F -value, and also in the population-corrected value of the coefficient of determination $\widetilde{R}^2$. Furthermore, it even affects the possibility of solving the system of normal regression equations itself. As mentioned beforehand, aspects related to inference and population correction are particularly crucial in design endeavours. It should also be considered, as illustrated in Figure 7-3, that the decrease in the value of $\widetilde{R}^2$ accelerates when the number of variables is close to the sample size, particularly when the values of the original R^2 are low. Therefore, in these scenarios, a reduction of the sample size in just a few individuals can have a remarkably negative effect in the inference capabilities of the model.

An additional insight on the behaviour of this mutual influence of the number of variables with the sample size must be highlighted. This aspect is related to the differences on the

impact that this issue has on the model depending on the type of statistical technique that is being used, namely, whether bivariate or multivariate approaches are employed. The matter to be expounded here is illustrated through a practical scenario in Figure 7-13 to support the following discussion.

In the case that is being formulated following the figure, an initial data matrix is assumed which spans twenty aircraft and four different variables. This table has some missing data values, as seen in the red cells. If a multivariate method were to be conducted on it, any aircraft that have just a single missing value would need to be discarded from the set, as the statistical analysis demands a full dataset to operate. The final data matrix to conduct the analysis is represented by the blue rows, resulting in only six aircraft. This is a notably low sample size which could potentially yield issues in terms of inference.

Now, starting from the same data matrix, the use of a simple linear regression approach is proposed. This method falls within bivariate procedures, so at each step of the analysis it can only cover two variables simultaneously. This is a typical process in statistical approaches both in the areas of manned and unmanned aircraft design, where even if a dataset spanning different variables is available, instead of analysing the interdependence among all of them at the same time, they are evaluated following a consecutive order in groups of two so as to obtain the most adequate regression for each pair (42; 46; 104; 360). In this case, the data matrix of each application case only spans two variables at a given time, so there is a higher probability that each aircraft can be kept in the model, as now each individual only needs to have the two variables relevant to each analysis step. With this, it can be seen that the data matrix for each of the three simple regressions always has a larger sample size than the full one studied through a multivariate approach.

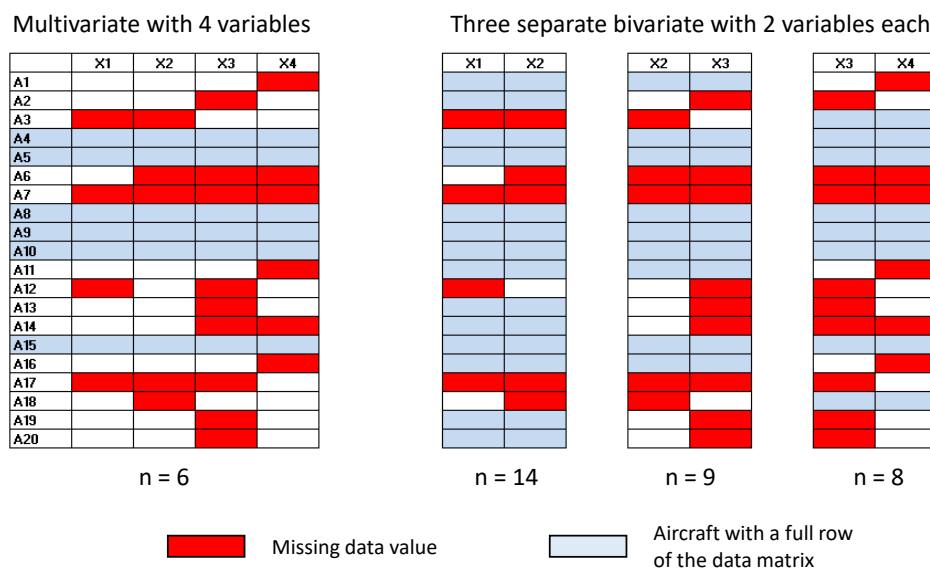


Figure 7-13. Illustration of the ways in which the lack of data cells impacts the resulting data matrix depending on the type of statistical approach: multivariate or bivariate.

Therefore, it can be seen that the requirement of a full data matrix has a different impact in each case, with overall the bivariate sequential analysis being more robust. However, this only constitutes an illustrative example, and further scenarios could yield distinct results depending on many factors, such as if the variable with the most amount of missing data is dropped from the multivariate approach. Furthermore, the results from each case shall be different, as the individuals which have to be dropped depend on the way in which the missing values are distributed along both the dimensions of variables and individuals. In any case, it can be seen that the behaviour commented here shall have a decisive impact on the analyses to be conducted in this chapter, and must be kept in mind to plan the scope of the statistical approaches to be employed.

Using various sources of information and measuring certain variables in three-view drawings are some measures that have been adopted in this chapter to mitigate the aforementioned challenges. However, from a general standpoint the designer does not have much control over the challenges commented here, as they are mainly dependent on the amount of data which is made publicly available. A potential approach to mitigate the impact of missing values in the dataset is to perform an imputation of values in the missing cells, which was used in a previous work within this field, precisely before applying the factor analysis process (61). However, it is often difficult to unveil the underlying trends employed to perform this imputation, and even when they exist, the results obtained might not be completely satisfactory.

Overall, the challenges mentioned in this section shall constitute key aspects to be considered through the analyses to be conducted within this chapter. In particular, the choice on both the number and the particular variables to be included in the model is a key aspect that will be taken into account particularly when applying the factor analysis approach. In view of the challenges commented here, it can be argued that these may have been among the reasons for previous works not having estimated trends for certain variables. Thereby, it might be said that these issues could be a root cause of some of the specific gaps in this area as already commented in chapter 2, allowing at this point to give a more accurate answer to the findings already outlined at that point.

7.6. Regression analysis results and design methodology

This section expounds the first of the two analytical procedures followed to study the RPA database compiled in this work. Here, the results will be obtained mainly through the use of regression analysis, which as mentioned beforehand is a classic procedure in previous statistical approaches for manned aeroplane and RPA design. A sequential bivariate approach will be followed, which is also the usual process in previous studies, and it is also less affected by missing data at each step of the analysis when compared to multiple regression or other multivariate approaches. As laid out in the introduction, the purpose is not only to extract separate trends among relevant design variables from the database, but to then use all of the obtained statistical results to assemble a systematic geometric

sizing workflow which can be used to produce a first estimation of the aircraft geometry within the first steps of conceptual design.

Before extracting results from the database, it is first required to select the sub-dataset which is going to be employed in this study, which also includes the choice of the classifications to be employed. This step shall be conducted in 7.6.1. Then, the results from the regression analysis shall be expounded in subsection 7.6.2. These are also accompanied by a set of univariate results in the form of histograms to aid the designer in selecting typical values for certain design variables where meaningful regressions were not found. Then, subsection 7.6.3 leverages the design trends extracted beforehand to generate a geometric sizing workflow, which is then tested in three case studies within subsection 7.6.4.

7.6.1. Sub-dataset selection

As seen from the overall database descriptive results in 7.4.3, the aircraft that been compiled within it show a significant diversity in many aspects: powerplant type, aerodynamic layout, tail union with fuselage, etc. As mentioned at that point and also in 7.5, seeking to obtain meaningful statistical results for the whole dataset could result in a significant scatter, since there are many sources of variation affecting the distinct datapoint. Even if trends are observed, they might not accurately represent with accuracy the design variations of these aircraft, and thus their use in design procedures might be hindered. This aspect has been highlighted in previous research within the field of RPA statistical approaches (40). This matter is even more significant when considering that the objective here is not only to obtain descriptive trends of the sample of RPA compiled in the database, but to ensure that these results can be inferred to the overall RPA population, particularly since the regressions must also serve to conduct the initial sizing of new RPA not included within the database, and therefore outside the considered sample.

Taking into account these considerations, before delving into the regression analysis process, it is first required to select which sub-dataset is going to be studied here. The following points summarise the main aspects which have been taken into account when making this decision, which are substantiated both taking into account the previous discussion through this chapter, as well as findings of former works in the state-of-the-art:

- It would be advisable to consider the powerplant classification, as it has been seen in the work of Palmer (36), that typical values of design parameters such as the wing loading show meaningful differences as a function of this categorisation. Furthermore, in the research of Verstraete and colleagues (39) it was seen that separating the RPA of the database attending to their powerplant yielded significantly different regressions in relation to mass and geometric variables such as the *MTOM*, wingspan and wing surface. Thereby, attending to previous

experience, it appears that performing a classification by powerplant is a must to ensure that adequate trends are obtained, as already commented in 7.4.3.

- At the same time, the use of the general configuration classification fits with the overall objectives established for this chapter, which places emphasis on variables related to the tail surfaces, necessitating to use this criteria to study the diverse tail configurations seen in these aircraft.
- However, the use of two classifications might reduce the sample size of each sub-dataset, which must be carefully observed through the statistical metrics. Furthermore, some of the groups resulting from the application of these two criteria through the entire database might be reduced so much that it would be unfeasible to obtain feasible statistical results. This could be the case, for instance, of tailless RPA with turbine engines. However, since the methods developed in this thesis seek to have an ample applicability range, these resulting sub-datasets with very few datapoints can be considered to fall outside the scope of the methods that are sought here, so the focus shall be on the most sizeable groups, which are not only the most representative of current RPA designs, but it is also expected to enhance the statistical results, as a larger starting sample might be able to withstand the effect of missing data more effectively, as developed in the previous section. The criteria employed here of focusing on categories with higher sample values rather than on those which might push the limits of statistical significance or showing a large scatter has also been followed within previous works in this area (35).
- The point above must be balanced with the need for the methodologies to also cover various RPA types, for instance, those showing distinct general configurations. In view of the diversity of RPA design, it is key that the methodologies used by the designer cover various possible design solutions, to aid in the choice of the most promising ones in the initial stages. This point has been highlighted in the broad field of RPA (21) and also in the realm of computerised environments (70).
- The reciprocating engine powerplant type is not only the most sizeable one within the database, but it is also seen through the largest range of MTOM. In contrast, albeit the electric powerplant category includes a non-negligible number of aircraft, they are mostly restricted to MTOM values below 10 kg. Furthermore, in previous research it has been seen that the regressions obtained for RPA with these powerplants are generally weaker when compared to those of other engine types (39). Thereby, the study to be conducted here shall focus on the reciprocating engine RPA, following with the objective of obtaining results with broad applicability and also to ensure the goodness of fit of the statistical results.

Considering all of the above points, the sub-dataset selected to perform the statistical analysis of this section has been the group of RPA with reciprocating engine and showing configurations of the following types: conventional tail, T-tail, V-tail, and H-tail. As it will be seen, even some of the groups resulting from the intersection of these two categories already have a low sample size in some cases, such as when analysing the variables related to the tail surfaces, since few data has been found for these parameters as seen in Table 7-3, so for other configurations which have not been included here, which have an even lower number of aircraft, the sample size issue would be even more complex to manage.

The selected configurations, as seen in Figure 7-7, represent the most sizeable ones in the current state-of-the-art, thereby allowing to obtain more significant statistical results and also having a broader applicability range. This is also aligned with one of the key points for the future development of methods to be integrated within computerised environments as laid out in 4.6.2, since the selected configurations correspond to the most widespread ones in RPA, solving one of the issues of the current landscape of RPA design packages. Furthermore, these configurations have also been the ones for which most three-view drawings were found, so they are the ones where more tools have been found to mitigate the data scarcity issues which must be managed to obtain satisfactory statistical results.

7.6.2. Regression results and histograms for specific design variables

This subsection presents the results from the statistical approach based on regression analysis performed in the sub-dataset selected beforehand. As mentioned at the start of this section, the final purpose of these results is their use in establishing a geometric sizing workflow for the initial steps of RPA design. However, the trends that will be shown here also have use by themselves, as they represent design trends in existing RPA. Furthermore, since statistical aspects related to inference will be observed through the results obtained here, these trends could also be generalised to the population, increasing their reusability. As mentioned beforehand, in some cases where meaningful regressions were not found, univariate analyses have been performed. In both classic and recent references from aircraft design, these also constitute a proven approach to aid the designer in selecting the values of certain variables within the first design steps (8; 11; 42; 44; 48).

A summary of the main criteria employed through the regression analysis process is given in the following points:

- The selection of the variables to be studied towards presenting their regressions here is mainly based in two criteria. They seek that the results are supported by both aircraft design and statistical considerations:
 - From the aircraft design standpoint, the studied trends must reflect reasonable connections between design variables which can be explained

through the aircraft design knowledge. For instance, a $S_w - MTOM$ regression is related to the wing loading design parameter.

- From a statistical viewpoints, the regression must yield results which support is goodness of fit to the data. This shall mainly be done by observing the metrics obtained from the regression statistical analysis, such as R^2 and $RMSE$. Furthermore, for all regressions included here, the statistical significance tests mentioned in 7.4.1 have been checked and only those where the inference at the 10 % level of significance is supported have been kept.
- The selection of the variables to be studied has been attending to both the usual parameters considered in the initial stages of aircraft design and also to the objectives of this chapter, which emphasise the analysis of tail surface and fuselage parameters. At this stage of design, only general variables related to these components tend to be considered, such as the surface areas or lengths, as seen in previous works (42; 44). This constitutes a novel contribution of this study, since these type of variables have seldom been considered in previous RPA statistical analysis works.
- Considering the influence of the sample size on the statistical metrics, whenever possible it has been prioritised to keep all five layouts in the same category and obtain the statistical results for their ensemble. The results shown here have only separated the different tail types when it was seen that the results of each of these groups differed significantly from the ones obtained for the whole set. Therefore, when various tail types have been jointly within the same regression or histogram category, this has been done after checking that no significant separate trends exist. Prioritising general trends when possible has also been a criteria used in previous research on RPA statistical analysis (39).

Before moving forward, it is highlighted that the number of data points varies among different regressions, and in all cases they are lower than the overall database size. This is substantiated when considering not only the sub-dataset which has been selected for this specific study, but also considering the fact that different data matrices for each pair of variables present distinct numbers and distributions of missing values. As brought forward in advance in Table 7-3, the analyses of variables related to tail surfaces and the fuselage can be expected to the ones with a lower number of points, since these are the variables for which finding data has been the most difficult, and in some cases, nearly no values would be available if measuring in three-view drawings had not been conducted.

The first regression corresponds to the relationship between the wing surface and the $MTOM$, as seen in Figure 7-14. This relationship presents a link with the classic design parameter of the maximum wing loading, which is defined as the quotient between $MTOW$ and S_w . It can be seen that the scatter is relatively low, albeit some points in the higher

MTOM range show a more noticeable distance to the regression line. In any case, some scatter is to be expected in this regression, as the wing loading has a tight relationship with many relevant performance aspects of the aircraft which may show a significant diversity depending on the design mission and category of the RPA, as it will be studied in further detail within chapter 8. In spite of this, the statistical results are satisfactory, as seen in the table footer.

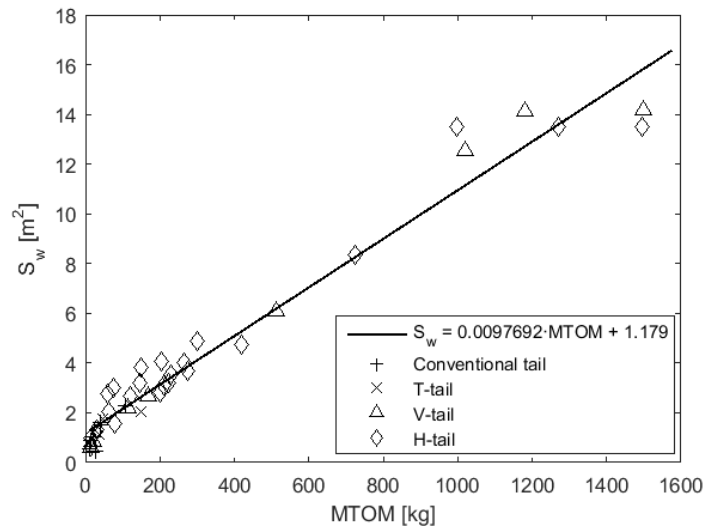


Figure 7-14. S_w – $MTOM$ regression for all sub-dataset layouts. $R^2 = 0.961$, $RMSE = 0.8465$.

The following regression, shown in Figure 7-15, has been obtained when considering the span loading parameter, $MTOM/b_w$. This quotient has been used in previous works for wing sizing, as and it is related to the vortex-induced drag of the wing, which has a significant impact in the drag polar of the whole aircraft, and thus in its performance (38; 392). Two distinct trends were observed when analysing the data points, with one corresponding to RPA that have lower values of AR , while the other one included RPA with high AR . When comparing aircraft with similar $MTOM$ values, the first ones also showed inferior integral performances in terms of range and endurance than the second, which could be expected, as a higher span loading is related to larger vortex drag.

From the designer's viewpoint, it could be argued that the second category, that of high AR , would always be desirable. However, many RPA are designed for tactical missions, with an emphasis on disassembly, transportation, and assembly in the operation area. From this viewpoint, wings with lower span tend to be advantageous, which would correspond to lower AR values. Furthermore, the wing structural design for RPA with higher AR wings is also more complex. Thereby, depending on a series of other factors, the designer might settle on a lower AR , thus this regression can also be significant from a design standpoint and has thus been included here. Another trend which has been observed is that the low AR category appears to be more frequent for lower $MTOM$ values, whereas in the case of RPA with large $MTOM$, which usually have more stringent performance requirements, the high AR group becomes predominant.

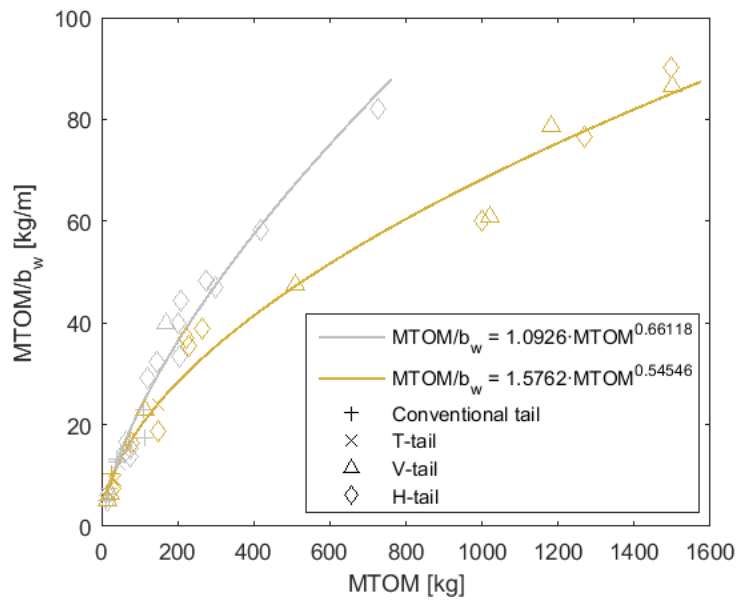


Figure 7-15. Span loading – MTOM regression for all sub-dataset layouts, with high Aspect Ratio ($AR \geq 11$) for the golden curve, with $R^2 = 0.969$ and $RMSE = 3.54$, and low Aspect Ratio ($AR < 11$) for the silver curve, with $R^2 = 0.979$ and $RMSE = 4.34$.

To finish the design process of sizing the equivalent wing, a value for the taper ratio should be selected. As seen in the equations formulated in 7.4.3, the equivalent wing taper ratio depends on the characteristics of the original wing, with these being a function of their planform and the number of trapezoidal segments that constitute them. Thereby, even if all database equivalent wings are straight-tapered ones, it can be expected that different trends in the taper ratio will be observed depending on the original wing planform. This is shown in Figure 7-16, where it is however observed that both straight-tapered and semi-tapered show an overall similar distribution. If the designer has already chosen the final wing type, then a suitable final for the equivalent wing aspect ratio can be chosen which is compatible with the final planform to be defined later on.

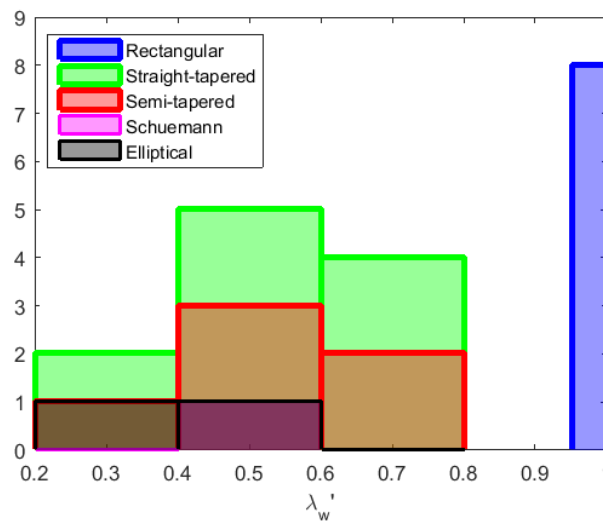


Figure 7-16. Histogram for the equivalent wing taper ratio attending to the original wing planform area. All rectangular wings and straight-tapered ones have a direct correspondence to the original wing, with the rectangular ones all showing a unit value of taper ratio.

Now, regressions corresponding to the process of tail sizing shall be extracted. The first of these is shown in Figure 7-17, and it is obtained between the wing surface, S_w , and the HTP surface, S_h . Here, the layouts of conventional, T- and H-tail are considered. As seen below, all fall within the general overall trend, with relatively reduced scatter save for a couple of points. This type of regression is related to the S_h/S_w quotient, which has been used in previous work on manned aeroplane design (7; 8). In the case of previous works in the area of RPA, similar regressions have not been found in the state-of-the-art for HTP sizing, so this regression can be considered one of the original results of this line of research.

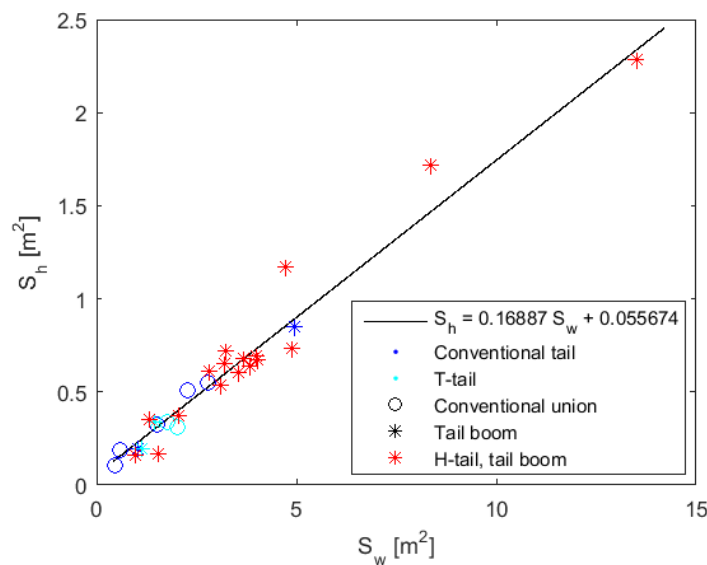


Figure 7-17. $S_h - S_w$ regression for conventional tail, T-tail and H-tail layouts.. $R^2 = 0.975$, $RMSE = 0.100$.

The following step related to the tail design refers to its location with respect to the wing, which is usually measured through the horizontal tail volume coefficient, V_h . In manned aeroplane design, this step is usually undertaken through the so-called “V-method”, which is based in the selection of a volume coefficient coherent with that of similar aircraft (8) (11). In previous works of RPA design, only two sources have been found that have studied the volume coefficient trends, which are those of Barnhart and colleagues (4) and Götten and colleagues (116). Each of them gives a typical value of V_h for RPA, but no other comments with respect to the distribution of this variable through different designs, or its potential differences between diverse RPA types are given.

Here, a histogram has been obtained to showcase the distribution of values of V_h , which is shown in Figure 7-18. Here, it is seen that there is a significant amount of scatter in both aircraft groups. The trend and distribution of conventional and T-tail has certain differences to the one followed by H-tail ones, with the latter one showing a more spread out distribution overall. The values obtained by previous authors fit within the modes of each of the groups represented here, however in those cases the distribution of the values were not provided, which is an information that is shown here. Due to the scatter of the V_h , it is recommended to use this histogram along with the value of the volume coefficient of similar aircraft to the one which is going to be designed.

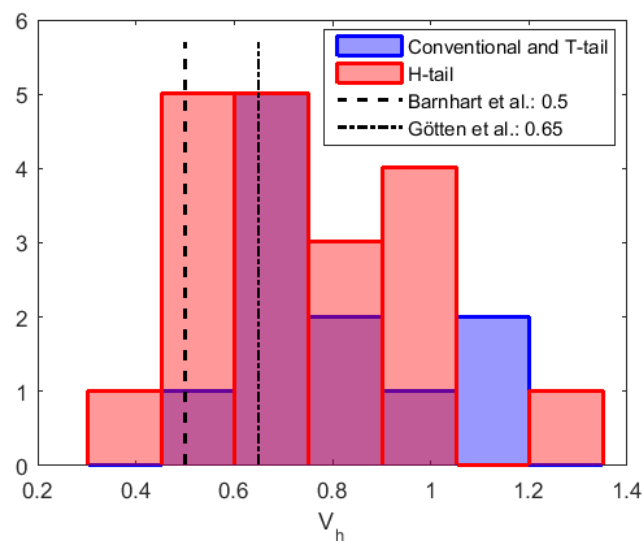


Figure 7-18. Histogram for the horizontal tail volume coefficient attending to the tail type. The values proposed in previous works have been represented as vertical lines.

Moving on to the sizing and location of the VTP for these aircraft types, the first step proposed here would be to locate it with respect to the wing. As the position of both HTP and VTP usually presents a geometric interdependency, this shall be used to obtain a regression that links the HTP moment arm, L_h , with that of the VTP, L_v . Since the volume coefficient of the HTP has been obtained at this point, the value of L_h can be derived from it, allowing to enter the regression shown in Figure 7-19. In this case, a classification

depending on the relative position of the HTP has been used to obtain two regressions with higher accuracy. Conventional tails would correspond to low HTP positions, T-tails with high HTP locations, and H-tail ones could fall within each of the two categories depending on the designer's choice.

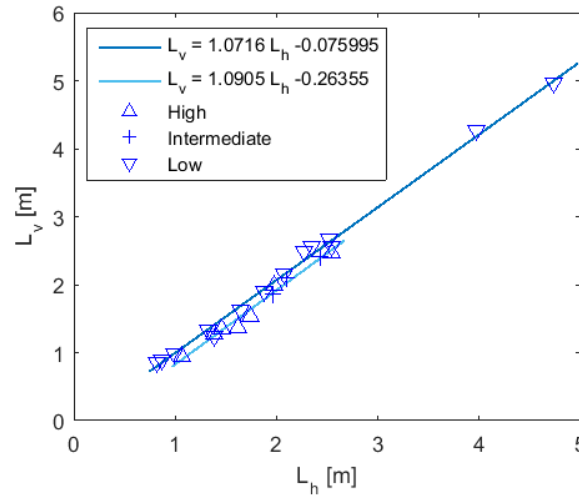


Figure 7-19. $L_h - L_v$ regression for conventional tail, T-tail and H-tail layouts, with the top curve corresponding to low HTP positions, with $R^2 = 0.997$ and $RMSE = 0.080$, and the bottom curve corresponding to intermediate or high HTP positions, with $R^2 = 0.978$ and $RMSE = 0.080$.

Having located the VTP, its overall size would now have to be obtained. In the case of RPA, most of them have only one engine which is located in the plane of symmetry of the aircraft. Therefore, and in contrast to the prevalent criteria in transport manned aeroplane design, VTP sizing here would not depend on lateral-directional control in the event of engine failure, which is also a similar scenario to many ultralights and some normal category manned aircraft (7; 8; 9). Therefore, the “V-method” is once again followed, with the results for the vertical tail volume coefficient, V_v , being shown in the histogram of Figure 7-20. It is noted that the S_v considered in the database for H-tail RPA has been the total of both VTPs. Once again, it is seen that there is a significant scatter, particularly for the H-tail. The typical value proposed by previous works can be considered to be more or less aligned with the overall trend, but aspects related to its distribution and the differences between tail configurations were not provided at that point.

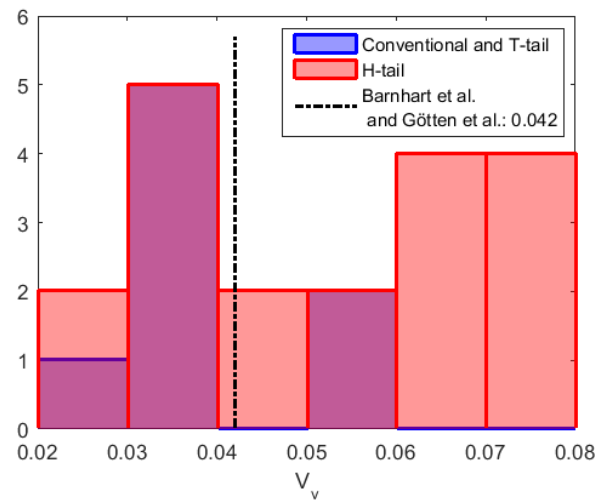


Figure 7-20. Histogram for the vertical tail volume coefficient attending to the tail type. The values proposed in previous works have been represented as vertical lines.

Moving on to the V-tail category, the tail sizing of these type of RPA has not been tackled beforehand within the state-of-the-art, so the results presented here would constitute novel contributions of this thesis. Firstly, a regression to obtain the overall surface of the V-tail, S_{vee} , is proposed, following a similar line of thought to that which was followed with the HTP sizing. Here, it is noted that this surface corresponds to the real magnitude of the overall tail, and not to its projections in either the horizontal or vertical planes. The results are shown in Figure 7-21.

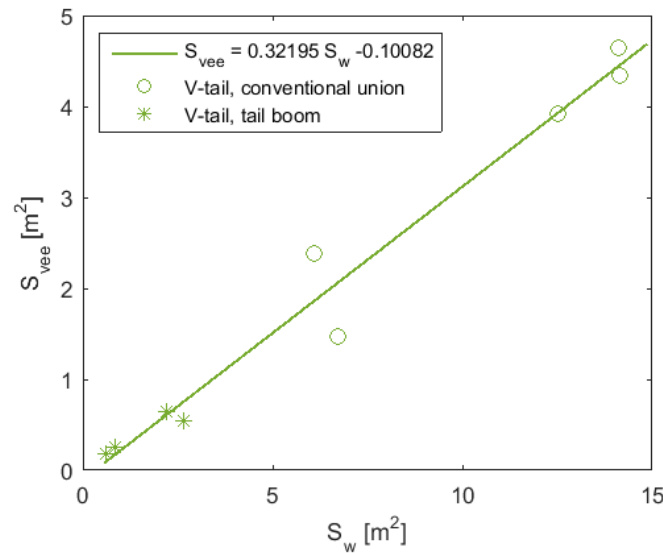


Figure 7-21. $S_{vee} - S_w$ regression for V-tail layouts. $R^2 = 0.973$, $RMSE = 0.324$.

To complete the V-tail positioning, its volume coefficient, V_{vee} , shall be employed. In contrast to the previous cases, here a meaningful regression has been shown obtained through the use of the numerator and denominator of the tail volume quotient, as seen in with L_{vee} being the moment arm of the V-tail. The values of V_{vee} for the different aircraft in the database have all been found to fall in the 1 - 1.3 interval.

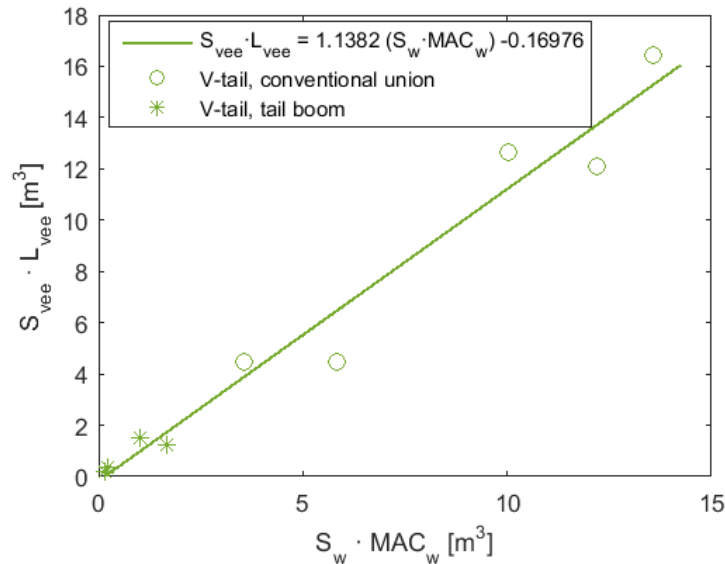


Figure 7-22. Regression related to the V-tail volume coefficient, with the predictor variable representing its denominator and the response variable its numerator. $R^2 = 0.964$, $RMSE = 1.26$.

Once the areas of the main aerodynamic surfaces have been studied and the tail surfaces have been located with respect to the wing, the next step would be to obtain an initial description of the fuselage and tail boom characteristics to complete the initial sizing. At this design stage, this can be accomplished by obtaining values for the fuselage length, l_f , tail boom length (where applicable), l_b , and the slenderness of both of these elements, λ_f and λ_b respectively. These variables are also the main focus of statistical analyses focusing on the initial steps of the conceptual design phase, such as in the recent works of (42; 44). A more refined geometry of the OML of these elements, particularly taking into account the nose and rear-end geometries, would be defined in further steps of the conceptual design phase.

To this end, firstly, a regression has been obtained for the fuselage length, which allows to obtain it from the tail moment arm, L_{tail} . This latter variable would correspond to L_h for conventional tail, T-tail and H-tail layouts, and to L_{vee} for the ones with V-tail. The regression is shown in Figure 7-23. In these case, no differences were seen among tail types, however there is a strong difference when comparing different kinds of tail union with the fuselage, which as commented in 7.4.3 was one of the categories that would be considered at certain points when needed.

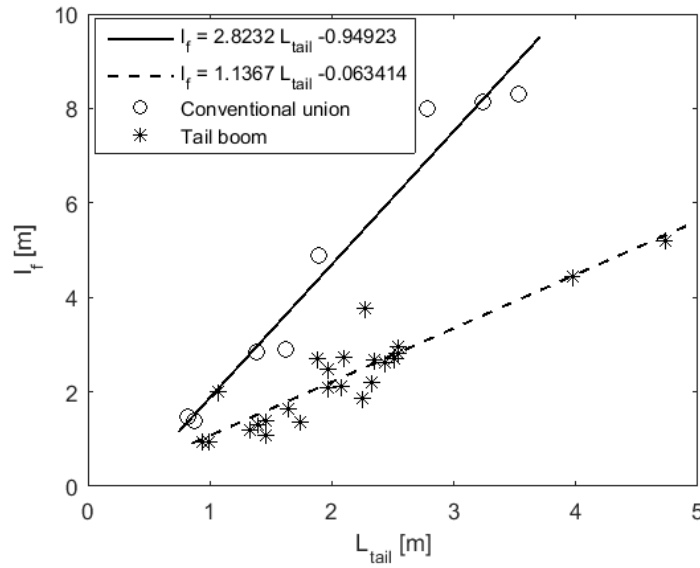


Figure 7-23. $l_f - L_{tail}$ regression attending to the tail union with the fuselage, with the top curve corresponding to a direct union, with $R^2 = 0.961$ and $RMSE = 0.645$, and the bottom curve corresponding to a tail boom union, with $R^2 = 0.836$ and $RMSE = 0.446$.

As it can be seen, while the conventional union regression line shows a good fit to the data points, the metrics related to the tail boom one are worse than those of the regressions which have been obtained until now. Therefore, it is proposed to use a different approach to size the fuselage of RPA with tail boom union. As a first step for this, the total length of the aircraft is estimated attending to the tail moment arm, as it can be seen in Figure 7-24. It should be noted that, in the case of aircraft with conventional tail union, $l \cong l_f$, but this is not the case in those with tail boom union, hence the different results which are observed in this figure. However, it can be checked that the quality of the regression is much better in this case, so instead of using the previous correlation, this shall be the one proposed as the initial step in fuselage and tail boom sizing for this kind of aircraft.

Once the overall length of the RPA is known, the quotients l_f/l and l_b/l would allow to size the length of both fuselage and tail booms. From the aircraft in the database, it could be seen that these parameters seem to be selected in a comparatively ad-hoc manner for each individual RPA, with significant scatter and no clear underlying trend being observed. Therefore, it is recommended that these quotients are selected attending to similar aircraft to the one which is being designed.

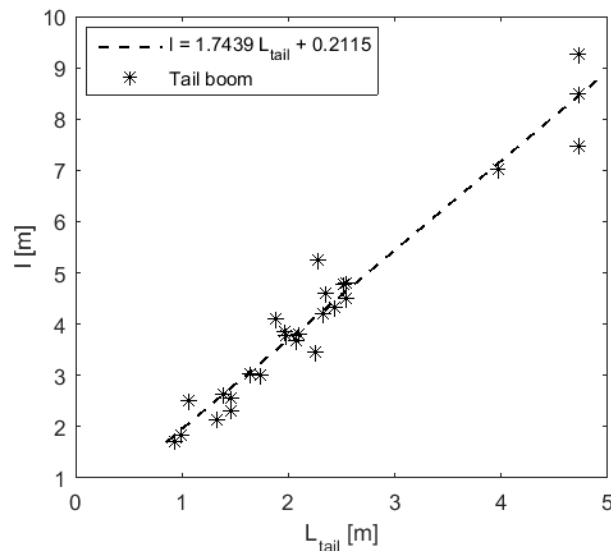


Figure 7-24. $l - L_{tail}$ correlation for all layouts in the sub-dataset. $R^2 = 0.952$, $RMSE = 0.439$.

With the previous steps, either for conventional union or tail boom union, the lengths of fuselage and tail boom would have been obtained. The final step would be to select a value for the slenderness of both bodies, which would also in turn allow to estimate their overall diameter. The corresponding histograms are shown in Figure 7-25.

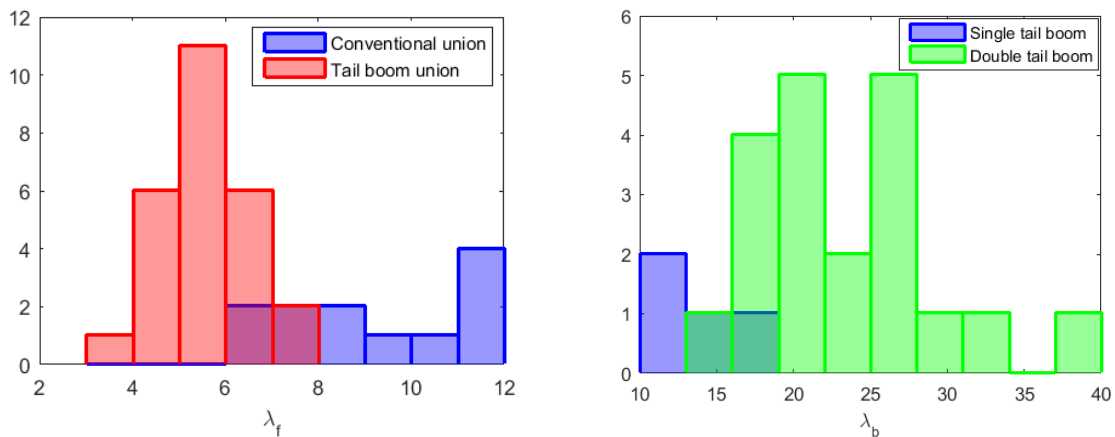


Figure 7-25. The left-hand-side figure is the histogram for the fuselage slenderness attending to the tail union type. The right-hand-side figure shows the histogram for tail boom slenderness, in which the two main types of tail boom configurations have been differentiated.

With respect to the fuselage, the slenderness of RPA with conventional union tends to be greater than that of those with tail boom. This can be expected as when the fuselage continues up to the tail, there is more volume available behind the wing to introduce the necessary equipments. However, in the case of RPA with tail booms, the fuselage usually finishes shortly after the wing's trailing edge, so a fuselage with a larger diameter would be needed to include all necessary equipment. Moving on to the tail boom union, there are

very few data points representing single tail boom unions, however it can be seen that they tend to present lower values of λ_b . This may be attributed to the fact that there is only one path to carry the loads from the tail to the rest of the airframe, so the tail boom may need a larger diameter to withstand them when compared to the double tail boom scenario, where there would be two load paths.

Before moving on to the proposed geometric sizing approach, it is highlighted that only those regressions with satisfactory statistical metrics have been included here. Other results were tested through this study, for instance with performance variables, and also including other parameters of the tail surfaces. However, the results did not reach the level of goodness of fit which has been shown through this analysis, in which the values of R^2 of those regressions to be used in the sizing approach have always been in excess of 0.95, and have generally shown low scatter. As it will be seen when conducting the case studies, satisfactory geometric sizing results have been obtained with the correlations obtained here. If other regressions with higher scatter or lower values of R^2 were included, then most probably the results would not fall within the expected accuracy of conceptual design. Most previous works within the topical area of RPA statistical analysis do not propose design workflows or perform case studies (39) (40), whereas in this thesis these aspects have been a priority, which is the main reason for the demanding statistical requirements that have been applied to the regression analysis performed here. Finally, it is highlighted that hypotheses tests for statistical significance according to 7.4.1 were performed on all regressions shown through this subsection.

7.6.3. Geometry sizing process for conceptual design

As commented in the introduction to this chapter, the final objective of the statistical analyses is to reach a series of empirical relationships which can be then sorted in a geometric sizing workflow for application in conceptual design methods. Thereby, this subsection proposes this sizing process by leveraging the results obtained in the previous one within a systematic workflow.

Overall, the geometric sizing process shall follow a similar flow to the order in which the different results were shown in the preceding subsection. The starting point shall be the value of $MTOM$ of the aircraft. Albeit this does not constitute an initial specification of the aircraft design process, it is intended that this geometric sizing procedure will be used within a broader initial sizing approach, which shall be done in chapter 9 where it is integrated within a design procedure that starts from mission specifications. Furthermore, similar geometric sizing approaches using correlations seen in previous research also start from this value (38; 42), since it is a representative design parameter of the aircraft as a whole.

The sizing process does not only consist in using the various correlations in sequence, as the designer's decisions have an influence in its flow at various points. The first of these is the selection of the qualitative layout characteristics of the aircraft, since the

correlations and histograms to be employed in each case depend on these factors. The choice of such aspects, such as the tail type, tail union with airframe, and also the vertical position of the HTP, are heavily dependent on each particular design case. Thus, the knowledge of the designer and the consideration of other aspects farther from those which are purely quantitative are required, as these are high-level decisions which affect the whole design process. The following references, which include both those related to manned and unmanned aircraft, offer some guidelines for making these overall configuration choices (1; 7; 8; 9; 10; 13). Chapter 10 shall also cover a quantitative approach for configuration selection which can complement the high-level considerations mentioned beforehand.

Furthermore, as mentioned beforehand, at some points the selection of a value for certain parameters would also be required to be conducted by the designer. The histograms provided in the previous subsection seek to aid in this process, which nonetheless should also be supported by the use of values from similar aircraft, which is also a very common practice in established methods for manned aircraft design (7; 8; 9).

The proposed geometric sizing workflow is shown in Figure 7-26, indicating the steps where correlations and histograms are used, as well as the points where the decisions made by the designer have a direct influence. It is highlighted that at every point where a regression is used, and to avoid extrapolation, the designer should verify that the predictor value falls within the interval range covered by the regression that can be seen in each of the figures provided through the preceding subsection. It is also noted that the wing planform generated through this process is always of straight-tapered one due to the use of equivalent wings with this geometry. However, the designer could then chose to generate a more complex wing shape which maintains the same wing surface, span, and MAC_w as the one generated through this process.

The design workflow proposed here would be one of the novel contributions of this thesis. Albeit as seen in both 2.4 and 7.2 there is a significant number of previous works within the GDM category in the RPA design state-of-the-art, only two of them have proposed a design workflow using the statistical results which they have obtained. The research of Agez (46) is focused on military RPA and it uses different classifications to the one employed here. The design workflow is mostly focused on overall aircraft parameters, and would not cover tail surface, fuselage, and boom sizing. On the other hand, the research of (38) is the one previously developed by the author with a former version of the database used in this thesis, where it only covered the H-tail layout sizing and various variables and design aspects where not considered at that point.

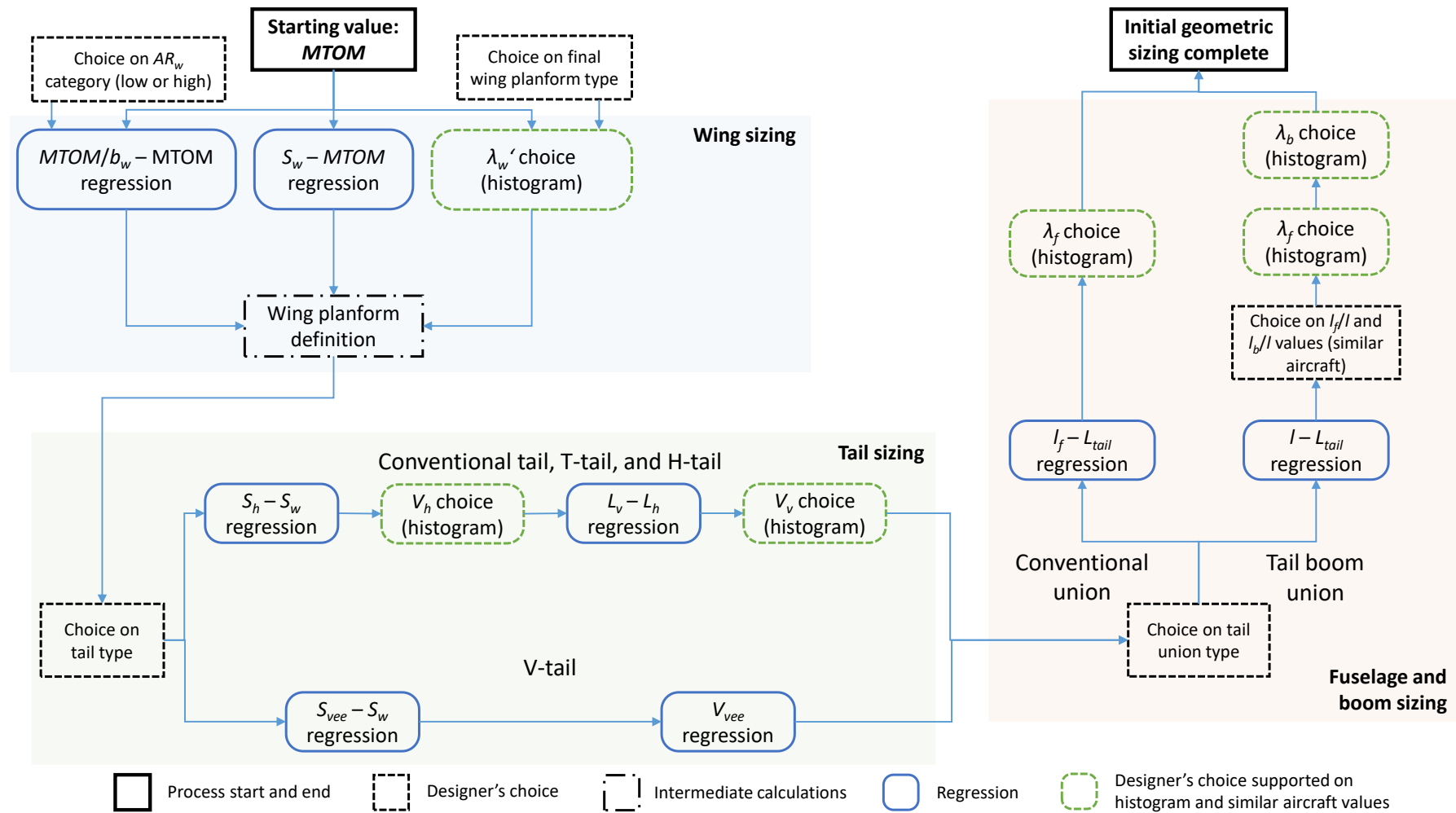


Figure 7-26. Geometric sizing workflow based on the application of the statistical results obtained through the regression analysis.

7.6.4. Correlation analysis method case studies

To test the performance of the geometry sizing process proposed in the previous section, three case studies will be conducted here. The process shall be to select three RPA which were not included in the database and measure them to obtain the real values of the variables involved in the sizing process. Then, using as a starting value *MTOM* and following the workflow illustrated in Figure 7-26, a series of estimated values will be obtained. These shall then be compared to the real values of the existing aircraft, so as to check the similarity between both pairs of values.

The RPA that were selected to conduct these case studies have been chosen to check various of the possible paths of the design process. Furthermore, as commented in 7.4.3, data availability was also a factor, since it was necessary to measure in three-view drawings so as to obtain all variables which are relevant in the process. The RPA are:

- **XPV-1 Tern:** with a *MTOM* of 59kg, conventional tail, and single tail boom union.
- **RQ-2 Pioneer:** with a *MTOM* of 205kg, H-tail, and double tail booms.
- **Hermes 450:** with a *MTOM* of 550kg, V-tail, and conventional union of the tail to the airframe.

At some points in the geometric sizing workflow, some decisions have to be made, and certain parameters have to be selected by the designer. These choices shall be made considering the RPA data available in the database, the histograms provided in this section, and the values of similar aircraft to the ones which are being designed.

The case study for the XPV-1 is shown in Table 7-4. Overall, it can be seen that the differences between the predicted values and the real ones would fall within the acceptable margin of error of the conceptual design stage. The category for the span loading correlation was selected as the low AR_w class, and the wing planform as rectangular since the XPV-1 Tern is a RPA without demanding performance requirements, and it is intended for rapid deployment on the field, and for easy manufacturing and replacement, with the selected categories matching that of the real RPA. Furthermore, as seen in Figure 7-11, the rectangular planform wing type is common for the *MTOM* range of the XPV-1 Tern. The choice of the values of V_h and V_v were based on both their histograms and on similar aircraft, and they also falls in line with the values provided by previous authors (4; 116). The highest errors are seen at the end of the sizing process for the fuselage and boom, particularly for their diameters. This could be expected as there is a higher scatter both on the correlations and histograms related to them. In any case, overall, the sizing of the geometry of this aircraft would yield a similar result to that of the XPV-1 Tern, so the results of the sizing process can be considered satisfactory.

Table 7-4. Case study of the geometry sizing process based on regressions for the XPV-1 Tern.

Variable	Units	Real value	Estimated value	Relative error
S_w	[m ²]	1.791	1.755	-2.0 %
b_w	[m]	3.450	3.644	5.6 %
Wing planform type	[-]	Rectangular	Rectangular	-
MAC_w	[m]	0.519	0.482	-7.2 %
S_h	[m ²]	0.362	0.352	-2.7 %
V_h	[-]	0.531	0.6	13.0 %
L_h	[m]	1.363	1.441	5.7 %
L_v	[m]	1.484	1.468	-1.1 %
V_v	[-]	0.038	0.036	-4.9 %
S_v	[m ²]	0.158	0.157	-0.4 %
l	[m]	2.710	2.725	0.5 %
l_f	[m]	1.577	1.430	-9.3 %
l_b	[m]	0.860	0.749	-12.9 %
λ_f	[-]	5.283	5.5	4.1 %
d_f	[m]	0.299	0.260	-13.0 %
λ_b	[-]	10.720	12.5	16.6 %
d_b	[m]	0.080	0.060	-25.1 %

The results from the case study corresponding to the RQ-2 Pioneer are shown in Table 7-5. Similar to the case of the XPV-1 Tern, this RPA is intended for tactical use and rapid deployment, which along with the performance requirements have led to the same choices of low AR_w class and rectangular wing. The histogram for V_v has been of fundamental aid in the choice of this variable, since the selected value, which is located in the area of higher values of the histogram as the similar aircraft fell in that zone, is quite different from that which is recommended by previous references, which would have given a very high error in this case. This supports the need of having information about the distribution of this variable, as well as the use of similar aircraft to make this choice in an accurate manner. The higher errors are once again found for the fuselage and tail boom sizing, but it can still be considered that the overall results from this sizing process are adequate for the conceptual design stage, providing an accurate initial point for future phases of refinement.

Table 7-5. Case study of the geometry sizing process based on regressions for the RQ-2 Pioneer.

Variable	Units	Real value	Estimated value	Relative error
S_w	[m ²]	3.181	3.182	0.02 %
b_w	[m]	5.130	5.557	8.3 %
Wing planform type	[-]	Rectangular	Rectangular	-
MAC_w	[m]	0.620	0.573	-7.6 %
S_h	[m ²]	0.591	0.593	0.3 %
V_h	[-]	0.659	0.65	-1.4 %

Variable	Units	Real value	Estimated value	Relative error
L_h	[m]	2.20	1.997	-9.2 %
L_v	[m]	2.20	2.064	-6.2 %
V_v	[-]	0.066	0.06	-9.1 %
S_v	[m ²]	0.50	0.514	2.8 %
l	[m]	4.370	3.694	-15.5 %
l_f	[m]	2.900	2.327	-19.7 %
l_b	[m]	2.210	1.847	-16.4 %
λ_f	[-]	6.776	5.75	-15.1 %
d_f	[m]	0.428	0.405	-5.4 %
λ_b	[-]	19.910	22.0	10.5 %
d_b	[m]	0.111	0.084	-24.4 %

Finally, the results for the Hermes 450 sizing process are shown in Table 7-6. In this case, the path of the workflow is different, since this aircraft a V-tail layout and conventional union, so the steps for boom sizing would not be applicable here. With respect to the wing sizing, the high AR_w category was chosen in this case due to the demanding performance requirements of the Hermes 450. Regarding the planform type, the $MTOM$ value of the aircraft would substantiate the selection of a straight-tapered wing when considering the results of Figure 7-11. However, the real aircraft has a rectangular planform. Nevertheless, this has not affected significantly the value of the MAC_w nor the rest of the values of the case study, which show a remarkable accuracy in this case, even for the fuselage sizing. This is owed to the reduced scatter of the $l_f - L_{tail}$ correlation which is employed in this scenario.

Table 7-6. Case study of the geometry sizing process based on regressions for the Hermes 450.

Variable	Units	Real value	Estimated value	Relative error
S_w	[m ²]	7.252	6.552	-9.7%
b_w	[m]	10.510	11.168	6.3%
Wing planform type	[-]	Rectangular	Straight-tapered	-
MAC_w	[m]	0.690	0.599	-13.2%
S_{vee}	[m ²]	2.153	2.009	-6.7%
L_{vee}	[m]	2.236	2.139	-4.3%
V_{vee}	[-]	0.962	1.095	13.8%
l_f	[m]	5.912	5.090	-13.9%
λ_f	[-]	11.24	10.0	-11.0%
d_f	[m]	0.526	0.509	-3.2%

In view of the results of the three case studies, it is relevant to highlight that overall there is a coupling of the errors through this process, since the values obtained as an output from one correlation are employed in subsequent steps of the workflow. Considering that some of the variables are obtained from a compound of various previous calculations, some couplings between the relative errors can be observed, which can at times amplify

the error of the variables. For instance, in the case of the RQ-2 Pioneer, the d_b has a relative error of -24.4 %. It is obtained by dividing the value of l_b (which has an error of -16.4 %) by λ_b (which has an error of 10.5 %). The fact that both relative errors have different sign amplifies the resulting error of the quotient, as the numerator is lower than that of the real aircraft and at the same time, the denominator is higher, leading to a lower overall result. A more thorough study of the statistical aspects related to this behaviour could be an avenue of future study in this line of work. In any case, as it will be seen in section 7.7, the design process that will be obtained from the factor analysis approach shows a distinct workflow without as many couplings, thus one of its advantages is that it mitigates the effect which has been observed here.

Overall, the results from the sizing process based on correlations are considered satisfactory for a method in the context of the first steps within the conceptual design stage. As mentioned in the preceding subsection, only two previous works within this topical area have proposed sizing procedures by leveraging their regressions, and in one of them a comparison with an existing aircraft was not conducted. Therefore, it can be considered that these steps which have been taken in the current work represent original contributions to the topical area in which they are contextualised.

7.7. Factor analysis results and design methodology

This section covers the application of the second of the two analytical procedures proposed in this chapter. In this case, the analysis and calculations shall be conducted through the factor analysis method, the theory of which was laid out in subsection 7.4.2. The application of this approach constitutes a novel contribution of this work, as only one of the state-of-the-art works analysed in 7.2 had used it, and in that case it was focused on the development of a pricing estimation approach, instead of in a sizing scenario.

As brought forward in advance both in 7.4.2 and in 7.5, the application of this multivariate approach to datasets with missing values presents its own set of challenges, as any aircraft just missing one of the values for any of the variables considered in the analysis would have to be discarded from the process. However, the potential advantages that can be reached through the use of this method are remarkable. Since it takes into account the ways in which the variances among the different variables interact, novel combined trends can be unveiled. Furthermore, owing to its rationale, the common factors extracted by this method can reveal original insights on the design patterns followed by the RPA included in the study. Aside from these results of the database trends, and in the same way as in the previous section, the purpose is not only to obtain the results of the statistical methodology itself, but also to derive a geometric sizing process from them, which is an additional step that will be taken in this study, along with conducting a case study to evaluate the performance of the proposed design process. Here, as it will be seen, the structure of the factor analytic approach allows to obtain a sizing method with fewer

sequential interactions, thus minimising at the design stage potentially adverse couplings between errors, which is considered to be an added advantage of this approach.

Before moving on to the application of the factor analysis approach, and in a similar vein to the steps taken in the preceding section, it is first required to select the sub-dataset to be employed here. Considering the data scarcity of some of the configurations used in the previous regression-based study, and taking into account the more complex scenario regarding missing data here, the forthcoming analysis shall focus exclusively on the H-tail layout with double tail booms. It was seen in 7.4.3 that this is the most sizeable category of the database, so the number of starting data points before accounting for missing data is larger, giving the sub-dataset a higher robustness, which is particularly useful in multivariate analysis scenarios. In contrast, as it was seen through some of the regressions and histograms of section 7.6, some of the other categories show a very low number of datapoints when analysing variables such as S_h or S_{vee} . This would require to reduce the number of variables that are considered, which would not allow to leverage the potential of this multivariate approach. As it will be seen further along this section, even when considering the H-tail layout which has a higher starting sample size, the resulting data matrix shall already be significantly reduced when including variables related to the tail surface size and position, so at this point it is not considered feasible to evaluate the other layouts with this approach. As both methods followed in this chapter (regression and factor analysis) are complementary, this constitutes one of the advantages of the regression-based approach, as also brought forward in advance in section 7.5.

Considering the above, subsection 7.7.1 shall first obtain the statistical results from the application of the factor analysis method. The empirical relationships obtained from this step shall then be used to derive a geometric sizing approach in subsection 7.7.2, which is then applied to a case study in 7.7.3.

7.7.1. Calculations, results and discussion

In this section the calculations of the factor analysis methodology shall be conducted for the RPA database introduced in subsection 7.4.3. This process will follow the overall roadmap expounded in 7.4.2 within Figure 7-6, which considers some particularities related to the use of the factor analytic approach to RPA design. The estimation of results that is expounded within this subsection is accompanied by their analysis and discussion under both the viewpoints of statistics and aircraft design.

Considering the requirement of having a full data matrix to conduct the calculations required by the factor analysis method, the H-tail configuration is the one selected, as substantiated above. The following step is to determine the set of variables to be studied through the application of factor analysis. The main challenge, as seen in Table 7-3, is that some variables tend to have a lower number of available data. Section 7.5 discussed the predicament of including within multivariate studies such variables, for which few data

points are known, along with others. Albeit the potential depth of the study and the conclusions that can be extracted is augmented when adding more variables, the reduction that the data matrix might see is in turn expected to be larger. A simultaneous increase in variables and a reduction in sample has an accelerated negative impact on the statistical significance of the results, as demonstrated through the equations of 7.4.1. Thereby, the selection of the variables to study is particularly critical in the forthcoming analyses.

Considering the above, it is proposed to conduct two separate studies applying factor analysis to a distinct group of variables in each case. The first one, named "**global design variable study**" will include fewer variables, but these shall be selected among those for which finding data has been more feasible. These are usually general variables describing the overall aircraft size, mass, and performance, which are the ones to have been more extensively studied in the preceding RPA statistical studied, as commented in 7.2 This decision is expected to avoid a large reduction of the data matrix in terms of sample size due to missing data. However, variables related to the tail surfaces are not included in this scenario. Thereby, this point is covered by the second case, named "**aerodynamic surface design variable study**", which shall include the tail surface features. As these variables are known for just a few RPA, the sample size will diminish considerably. However, the inclusion of more specific variables shall be key to develop a design approach that can also cover the sizing of these elements, which is one of the main gaps in the state-of-the-art. Both cases shall start from the sample size of the full sub-dataset of H-tail RPA with reciprocating engines, which consists of 88 aircraft. However, in each study the sample reduction due to missing values will result in a different size of the final data matrix.

There is one additional consideration to take into account when selecting the variables to be included in each of the application cases. This is that they should also comprise some parameters that can be used as starting steps of the geometric sizing process that will be generated from the factor analysis results. This sizing workflow, in a similar vein to that of 7.6.3, should commence with a variable whose value can be known by the designer before the geometric sizing process itself takes place. For instance, starting the sizing process from variables such as S_w or S_h would not be feasible, since these are not known by the designer at the onset of the development process, as they are precisely among the ones to be sized. Ideally, the sizing process should start from variables which constitute initial specifications of typical design process such as the payload, PL , cruise speed, V_c , or endurance, E . If this is not possible, as in the regression-based workflow proposed in the previous section, the value of $MTOM$ could also be employed, since it is a key design variable, and the sizing process to be proposed here will then be used further along the thesis within a design methodology with a broader scope which does begin from the initial specifications.

Overall, it is seen that the selection of variables to be included in the factor analysis model is not a straightforward task. As a summary, the following three aspects will be taken into account when making this choice for each of the two application cases:

- 1) The variables will be related to the focus of each of the cases. The one centered on global design variables is expected to include some such as overall length, l , wingspan, b_w , and cruise speed, V_c . In contrast, the application case focused on aerodynamic surface design will incorporate variables such as the wing surface, S_w , or the HTP surface, S_h .
- 2) The number and choice of variables shall take into account potential sample reduction issues due to data scarcity. This can limit the simultaneous consideration of multiple variables for which a lower number of data has been found.
- 3) The group of variables should include some that can be used as a starting point of a geometric sizing workflow, which is the final purpose of the factor analysis application as it which will be further developed in subsection 7.7.2. If these kind of variables are not included, then the common factor cannot be estimated from them, and they cannot be used as a starting point of the sizing process.

(a) Global design variable study

The first of the cases of study will be that of the general design variables. It is expected that taking into account characteristics for which data is readily available for many aircraft, the sample size shall be better than in the second scenario. This will also augment the confidence in the results, since it is more feasible to guarantee the population inference due to the higher sample size.

The features describing this study are the following:

- **Variables:** overall length, l , wingspan, b_w , Maximum Take-Off Mass, $MTOM$, Payload, PL , engine power, P_E , cruise speed, V_c , and endurance, E .
- **Resulting data matrix sample size:** 53 RPA.

As it can be seen, the sample size is lower than the one corresponding to the number of RPA with reciprocating engine and H-tail. This is due to some RPA not having the values for all of the considered variables. Even if data for the features selected here is more widespread, a missing value for any single one of these requires the aircraft to be discarded.

With respect to the variable selection itself, as mentioned before, here the emphasis has been in global variables which describe the main characteristics and performance of the overall vehicle. It has also been prioritised to choose features which are known for a significant number of aircraft so as to not penalise the sample size. The values of l and b_w

provide a general idea on the dimensions of the aircraft, *MTOM* is a relevant design mass which is also linked to key performance aspects of the aircraft, the *PL* is related to the mission sought to be achieved, the value of *P_E* can provide an initial estimation of the powerplant specifications, and both *V_c* and *E* are associated with the aircraft performance. Furthermore, it is highlighted that *PL*, *V_c*, and *E* have also been selected attending to the last of the third criteria mentioned beforehand, as they are related to the RPA initial specifications. It is not possible to foresee if they will show a strong correlation with the common factors, which is required to use them to estimate these factors, but they have been included in the case that this is finally possible so as to aid the development of the geometric sizing method later on.

Once the variables of study have been selected and the sample has been limited to the RPA with information on all of these parameters, the first step, consists in obtaining the correlation matrix. Already from this result, valuable insights relative to the interrelations of the observable variables among themselves, and thus regarding the global design interrelationships of these aircraft can be extracted. This matrix is presented in Table 7-7.

Table 7-7. Correlation matrix for the global design variables.

	<i>l</i>	<i>b_w</i>	<i>MTOM</i>	<i>PL</i>	<i>P_E</i>	<i>V_c</i>	<i>E</i>
<i>l</i>	1	0.888	0.942	0.842	0.919	0.552	0.670
<i>b_w</i>	0.888	1	0.928	0.917	0.822	0.568	0.830
<i>MTOM</i>	0.942	0.928	1	0.928	0.914	0.619	0.768
<i>PL</i>	0.842	0.917	0.928	1	0.859	0.563	0.769
<i>P_E</i>	0.919	0.822	0.914	0.859	1	0.578	0.593
<i>V_c</i>	0.552	0.568	0.619	0.563	0.578	1	0.565
<i>E</i>	0.670	0.830	0.768	0.769	0.593	0.565	1

Overall, the values of the correlation coefficients amongst the different variables can be considered as representing significant interrelations amongst them. Many of the terms of the matrix reproduce redundant interrelations, so the following comments shall prioritise those correlations with a direct physical interpretation will be highlighted, along with those cases which are most striking.

The high correlation coefficient of *MTOM* both with the length and the wingspan of the RPA reflects an increase in the general dimensions of the aircraft. Other authors have studied the regression of the value of *MTOM* with the general volume of the aircraft, obtained as the product of its height, length and wingspan (42; 360). This concept represents a proven trend in manned aircraft conceptual design can be related to the results obtained here. The correlation of *MTOW* with *PL* is also remarkable. As the aircraft requires to transport a higher payload, it is usually required to carry more fuel. Furthermore, the structural mass tends to increase along with payload and fuel mass as stated in (11). The correlation with the power of the piston engine is also noteworthy, which can be substantiated as broadly speaking a more powerful engine will be required

to surmount the higher drag generally expected from a larger aircraft. Furthermore, from the horizontal forces' equilibrium equation and assuming a similar aerodynamic efficiency, an increase on the aircraft weight would require more thrust. Regressions between these two variables have also been used in previous studies in the field of aircraft conceptual design (362).

The lower value of the coefficient of correlation with the cruise speed is considered to be due to the mission diversity within the RPA included in the database. Often, they are even stated to be multi-role aircraft. The cruise speed is mostly determined by the design mission of the aircraft, so it may be expected that the correlation with other variables is lower, as RPA with higher *MTOM* typically conduct missions at a similar speed to that of those with a lower mass. In order to verify this behaviour, a scatter plot is shown in Figure 7-27 for all H-tail RPA with reciprocating engines. It can be seen that the correlation amongst the variables is not particularly high, especially for aircraft above 400 kg, for which there is no significant increment in V_c with *MTOM*. This trend has also been analysed in previous studies in the field of RPAS (2; 35), thus it can be deduced that the value of the cruise speed is more strongly related to the requirements of the design mission of the RPA rather than to its *MTOM*.

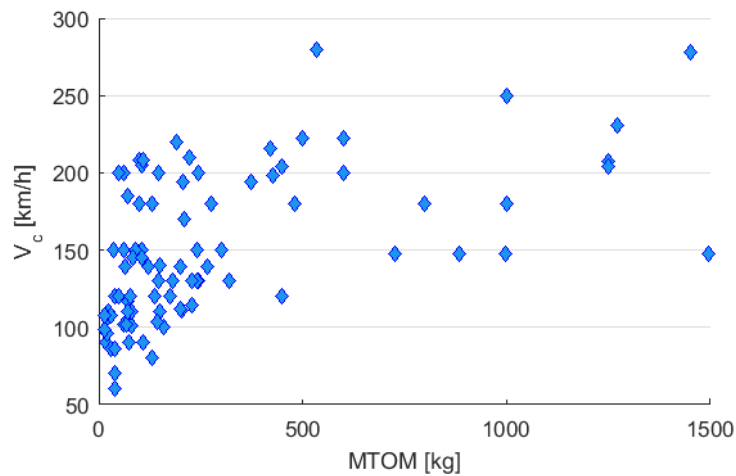


Figure 7-27. Depiction of the cruise speed (V_c) versus the Maximum Take-Off Mass (*MTOM*) for all RPA with reciprocating engine and H-tail.

One of the general conclusions which can be observed from Table 7-7 is that all of the correlation coefficients are positive. This shows that an increase in any of the considered variables is associated with a certain rise in the others. This can be deduced from the interpretation of the coefficient of correlation between two corrected and standardised variables, as is the case of this study, as the slope of the regression line corresponding to these parameters (379). This shows that there is a certain scale effect amongst the RPA included in the sample of study, which is a phenomenon that will be further explained when the factor extraction is undertaken.

The next step, as commented in subsection 7.4.3, is to estimate the communalities of each variable. This process shall be done through the multiple linear regression with the rest of the observed variables. The population inference shall be checked with the corresponding hypothesis test of equation [7-31], and the population correction of R^2 is also considered as seen in equation [7-29]. The results are shown in Table 7-8.

Table 7-8. Population inference statistical parameters for the communality estimation within the study of global design variables.

Variable	p-value	R^2	$\tilde{R}^2$
<i>I</i>	$1.25 \cdot 10^{-25}$	0.935	0.926
<i>b_w</i>	$4.69 \cdot 10^{-24}$	0.924	0.914
<i>MTOM</i>	$3.12 \cdot 10^{-30}$	0.959	0.954
<i>PL</i>	$1.10 \cdot 10^{-22}$	0.913	0.901
<i>P_E</i>	$1.20 \cdot 10^{-21}$	0.903	0.890
<i>V_c</i>	$1.09 \cdot 10^{-4}$	0.439	0.366
<i>E</i>	$9.16 \cdot 10^{-13}$	0.761	0.730

The p-values observed in the preceding table correspond to the probability of the hypothesis test when assuming a null correlation of one observed variable with the others, as stated in equation [7-30]. Most of these p-values are noticeably small, which would lead to a rejection of the null hypothesis considering the significance level of 5 % used in this work. With respect to their coherence with the values of R^2 , as it can be seen in equation [7-31], an increment in the coefficient of determination induces a larger critical value, resulting in lower p-values, being consistent with the results obtained here. Since these p-values are marginal with respect to the level of significance, it can be deduced that the population regression is statistically significant, and therefore it would be reasonable to infer conclusions regarding the population of RPA. Furthermore, even though the regression corresponding to V_c has a lower value of R^2 , the satisfactory sample size and strong interrelation amongst the variables allow to predict it as a function of the other characteristics with a satisfactory confidence.

Table 7-8 also shows the difference between the sample R^2 and the population $\tilde{R}^2$. As it is expected from the equation for a case with a large difference between the sample size and the number of variables in the study, and also considering the overall high starting values of the sample coefficient of determination, these values do not differ significantly, save in the case of V_c and E , which presented lower values of the sample R^2 . This general behaviour of the population correction can be demonstrated by representing the value of $\tilde{R}^2$ versus the number of variables and the original R^2 for a fixed sample size. This analysis is shown in Figure 7-28.

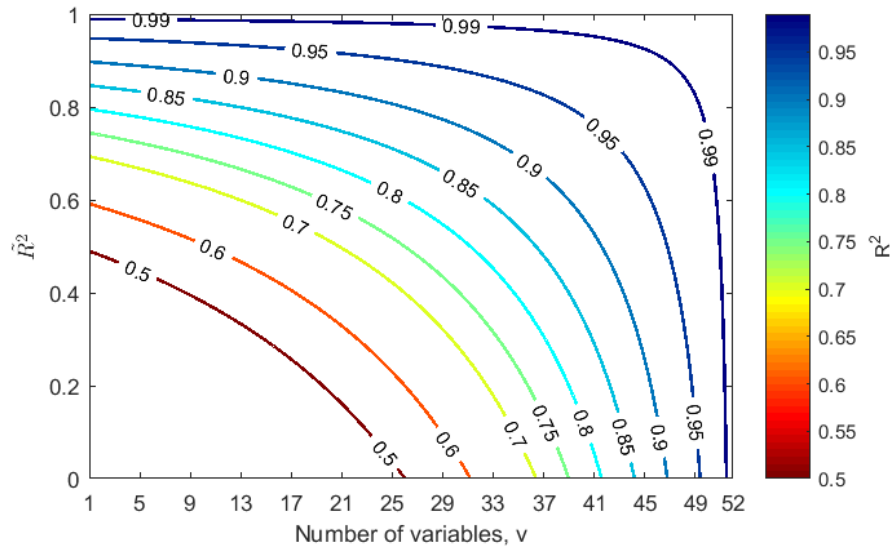


Figure 7-28. Representation of the population $\widetilde{R}^2$ versus the number of variables considered in the factor analysis study v and the original R^2 for a sample size n of 53 RPA.

Figure 7-28 shows that, when the number of variables is considerably lower than the sample size, the value of $\widetilde{R}^2$ does not suffer significant reductions with respect to the original magnitude of the sample coefficient of determination. When the number of variables is closer to the sample size, it becomes increasingly more relevant to start from a higher value of sample R^2 , since the reduction due to the population correction is more severe. The case of the global design variable study is a particular scenario of the aforementioned graph located at the horizontal coordinate of $v = 7$. Therefore, this type of representation can be useful to conduct the selection of the number of variables taking into account the sample size. In this case, since both values are far apart, a fine selection attending to this population correction behaviour was not required, but this graphical representation shall be extremely useful in the case study of advanced design variables due to the lower sample size that will be managed therein.

The insight which can be extracted from these results is that most of the variance of each of the observable variables can be explained through the changes that occur in the others. This can be concluded from the high values of the population $\widetilde{R}^2$, which correspond to the communalities. In the case of V_c and to a lesser extent E , the other variables included in the study do not suffice to explain most of the variations in these two.

The highest repercussion of these high communality values in the forthcoming factor analysis results will be that the common factors are expected to be able to explain most of the variance of the observable variables. This means that the specific factors will have a relatively low weight in the determination of the observable variables, as seen from equation [7-37]. This constitutes a significant benefit in the process of leveraging these factor analysis results to establish the geometric sizing process which is the main objective of this line of work, as for a new RPA not included in the database the values of

the specific factors would not be available. Furthermore, large communality values are often associated with a higher reliability of the measured variables, which also aids in augmenting the confidence in the results (393). One last point to be highlighted here is that the high values of the communalities can mitigate the issues associated with low proportions of sample size versus number of variables studied. As stated by previous authors, the strong interrelationships amongst the observable variables that are seen when most communalities exceed values of around 0.8 can aid in mitigating these difficulties (371).

Having determined the communalities, the following step consists in extracting the corresponding common factors for the observable variables to obtain the coefficients of the A_{vxq} and D_{vxv} arrays. Firstly, the number of factors to extract with the principal factor method must be selected. Two approaches shall be compared: the classical scree analysis (386; 387) which was expounded on in subsection 7.4.3, and the original method proposed in this chapter based on the analysis of the A_{vxq} matrix coefficients interpreting them as the correlation coefficients between the factors and the observable variables. The representation corresponding to the scree plot for this case is shown in Figure 7-29.

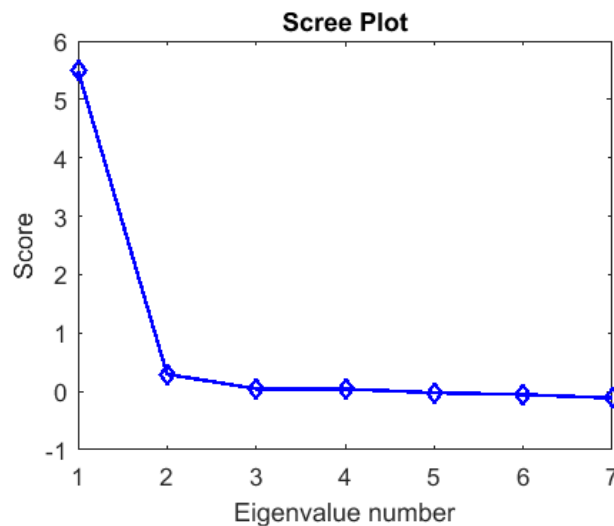


Figure 7-29. Scree plot for the factor extraction of the global design variables case study. The x-axis represents the number of the eigenvalue corresponding to each of the possible common factors when sorted in descending order of the associated score, with this latter value being represented in the y-axis.

The score of each eigenvalue is related to the amount of common variance that its associated factor can explain. Applying this scree test criteria, only one common factor would be retained, which is the one related to the first eigenvalue. Adding any additional eigenvalue would result in marginal increments of the common variance which is accounted for by the model, as seen in the small drops in the score that they represent. This would mean that most of the variance observed amongst the original variables could be described with a single common factor. This coincides with the trend observed in the

correlation matrix and the communalities, in that most of the variance associated with each variable can be described according to the changes of the others.

There is a result that can be observed in Figure 7-29 which should be highlighted, which is the fact that some eigenvalues have a slightly negative score. The reduced correlation matrix is symmetric; therefore, all eigenvalues are real. However, since it does not contain unit values in the diagonal, as these have been replaced with the communality estimations, some of these eigenvalues may be negative. This produces an effect called “Heywood Case”, which is substantiated in detail within references (370; 377). This phenomena is based on the fact that some positive eigenvalues overestimate the total variance in order to balance the negative ones that may appear when the matrix is not semidefinite-positive. Due to their lack of statistical and physical meaning, these are to be discarded. In this global design variable case, trying to extract a second factor, in spite of it accounting for only a marginal proportion of the variance, would already result in an overestimation of the total variance, falling within the aforementioned Heywood Case scenario, so in any case, the extraction of a second factor would not be feasible.

The findings from the scree test shall be compared with the novel method proposed in 7.4.2. The statistical significance of the coefficients of the A_{vxq} matrix corresponding to the extraction of the first factor shall be evaluated when considering them as Pearson linear correlation coefficients. The corresponding p-values are shown in the first two columns of Table 7-11.

Table 7-9. Coefficients of the factor pattern matrix associated with the extraction of one factor for the global design variables application case, accompanied by their corresponding p-values analysed as Pearson linear correlation coefficients. Results are shown for both the PF and Minres methods. The cutoff value for the coefficient for a sample size of $n = 53$ is of $r = 0.271$ in order to guarantee statistical significance with a 0.05 level of significance, which corresponds to the p-value limit for a F-Fisher one-sided test.

Variable	Factor 1 (PF)	Factor 1 (PF) p-value	Factor 1 (Minres)	Factor 1 (Minres) p-value
<i>I</i>	0.937	$5.07 \cdot 10^{-25}$	0.929	$1.01 \cdot 10^{-23}$
<i>b_w</i>	0.955	$1.75 \cdot 10^{-28}$	0.958	$3.24 \cdot 10^{-29}$
<i>MTOM</i>	0.985	$1.12 \cdot 10^{-40}$	0.994	$1.39 \cdot 10^{-50}$
<i>PL</i>	0.941	$1.00 \cdot 10^{-25}$	0.941	$1.04 \cdot 10^{-25}$
<i>P_E</i>	0.910	$4.23 \cdot 10^{-21}$	0.899	$6.98 \cdot 10^{-20}$
<i>V_c</i>	0.619	$7.62 \cdot 10^{-07}$	0.624	$6.13 \cdot 10^{-07}$
<i>E</i>	0.769	$1.05 \cdot 10^{-12}$	0.781	$5.13 \cdot 10^{-12}$

As it can be seen, the p-values associated with the coefficients of factor are once again marginal with respect to the level of significance. The statistical significance of these interrelationships can also be verified through the fact that the Pearson coefficients are always well above the cutoff value mentioned in the table header. Since the correlation of

this factor with all the observable variables is statistically significant, it is seen that the results of this methodology coincide with those of the scree approach, which also allows to validate this novel method proposed in the thesis.

Having selected that one common factor is to be extracted, and already having calculated its loadings in the previous step, the methodology of minimum residuals is now applied, with the initial value of the optimisation problem being taken from the PF results. Table 7-9 also includes the results of this Minres factor loading estimation method, which as it can be seen are once again all significant from a statistical viewpoint. With this, the variance accounted for by the factor common to all observable variables (the communality) and that which is associated to the factor specific to each of the variables (the uniqueness) can be obtained through the use of equation [7-36]. The results for the Minres method are shown in Figure 7-30, which also illustrates the percentage difference between the common factor loadings obtained by both methods.

The upper graph of the aforementioned figure is essential not only in the assessment of the statistical implications of the results, but also to study the feasibility of the factor analytic solution as part of the RPA conceptual design method which is the objective of the present line of research. As it can be seen, for l , b_w , $MTOM$, PL , and P_E , more than 80 % of their variance is accounted for by the common factor, and in the case of b_w and $MTOM$ it is higher than 90 %. Should the value of this factor be known for a new RPA to be designed, and neglecting the contribution of the specific factor (which cannot be known for an aircraft outside of the database), it would be possible that the results which may be obtained for the observable values through the use of the common factor could fall within the acceptable margin of error in conceptual design, most possibly below a 20 % error. However, in the case of the cruise speed V_c and the endurance, the variance accounted for by the common factor is much lower, so they may not yield adequate results when estimated through the common factor.

With respect to the differences between the results obtained with both factor extraction methods, it can be seen in the lower graph of Figure 7-30 that the results are notably close to each other. This aids to increase the confidence in the values that have been obtained.

Regarding the physical interpretation of the common factor, and attending to the notable correlations with the general dimensions of the aircraft (represented by its length and wingspan), as well as a high correlation with the mass variables and the engine power, the conclusion which has been reached is that the factor represents in a certain sense the overall scale of the RPA. This can also be seen through the fact that the correlations of the factor with all of the aforementioned variables are positive. This means that as the factor increases the highlighted observable variables also rise with a significant slope of the linear regression represented by the Pearson correlation coefficient. This is in agreement to the aforementioned correlations seen in Table 7-7 between the length and wingspan variables (which represent the general volume of the aircraft) with $MTOM$, which coincided with trends observed by other authors (42; 360). For all of these reasons, it can

be concluded that this factor does in fact represent a scale or general size of the RPA, and hereafter it will be noted as f_s .

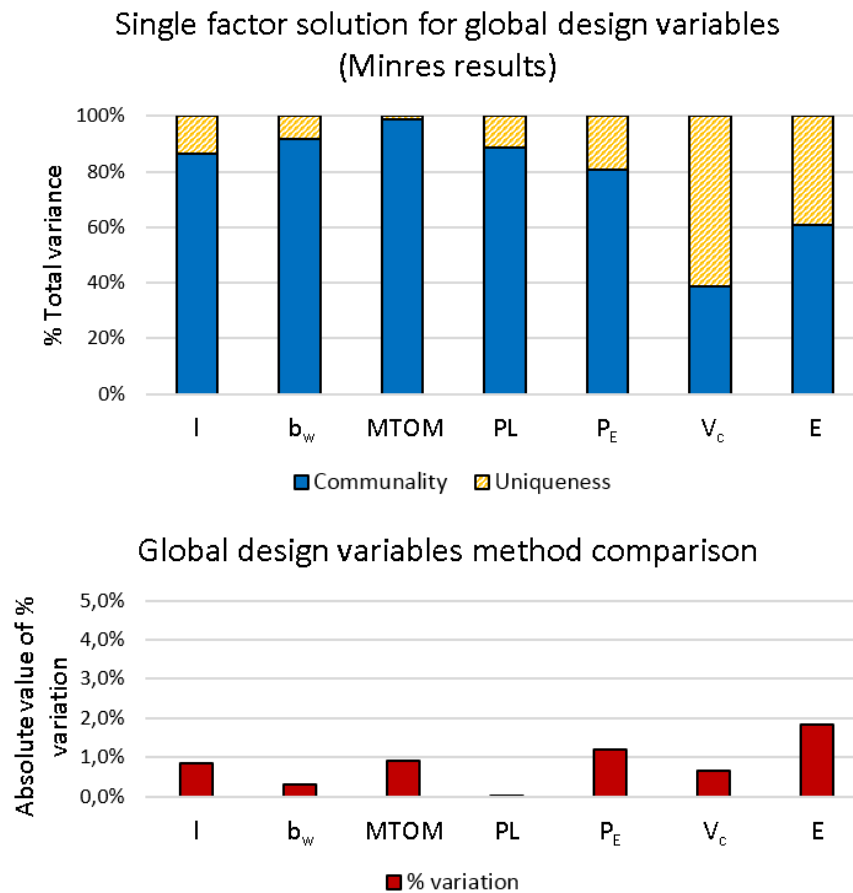


Figure 7-30. For the global design variable case, the graph above represents the variance accounted for by the common factor which is shared amongst all variables (communality) and the variance related to the specific factor particular to each of them (uniqueness). The graph below shows the percentage difference in absolute value between the application of the PF and Minres methods for factor extraction, calculated for each common factor loading.

The final step in the factor analytic process for the global design variables would be to obtain a method for the estimation of the common factor. Once this factor is known, this would then allow the designer to estimate the variables for which most of their variance is explained by this element (in this case: I , b_w , $MTOM$, PL and P_E). This can be achieved by applying the factor measurement procedure explained in subsection 7.4.2. The resulting coefficients for the β_{vxq} matrix, which represent the corresponding multiple regression of the factor with all observable variables, are illustrated in Figure 7-31. Since the coefficients have been obtained for the corrected and standardised variables, their magnitude is directly comparable.

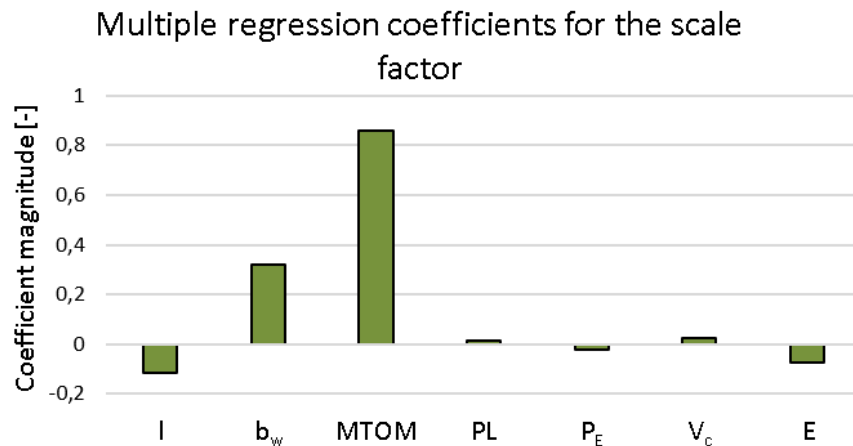


Figure 7-31. Multiple linear regression coefficients of the correlation to estimate the RPA scale common factor f_s as a function of the observable variables for the global design variables application case.

As it can be observed, the highest correlation coefficient is with the value of *MTOM*. On the other hand, and save for b_w , the correlation with the other variables is approximately an order of magnitude lower, so they do not determine in as much measure the value of the common factor. This agrees with the results of previous studies, where reliable correlations of *MTOM* to predict main dimensions of the aircraft such as the lengths and the wingspan were obtained, both in the realm of manned (42; 104; 360) and unmanned aircraft (39; 46). This means that the parameter *MTOM* explains most of the variance of the common scale factor, the other observable variables having a comparatively minor effect, since most of these variations are already accounted for by *MTOM*. This is advantageous from the standpoint of establishing this variable as the entry point of the geometric sizing approach to be proposed, since the objective of this step is to determine which of the original variables best describe the factor so as to then establish a regression between them with the factor, allowing to estimate the latter for a new RPA when the observable variables are known.

In view of the results, a regression shall be proposed for the estimation of the value of the scale factor, f_s , as a function of *MTOM*. This can be accomplished since the factor measurement step allows to obtain the numeric value of the common factor for all of the RPA within the data matrix, and from this point on it can be considered another variable which describes each aircraft along with the observable ones. Since *MTOM* is also known for them, the regression can be established. The use of the factor measurements in order to establish factor estimations starting from the observable variables has been proposed as an option in previous studies, however it was not conducted at the time (368). The resulting regression when accounting for the value of the scale factor which has been estimated for the sample RPA can be seen in Figure 7-32.

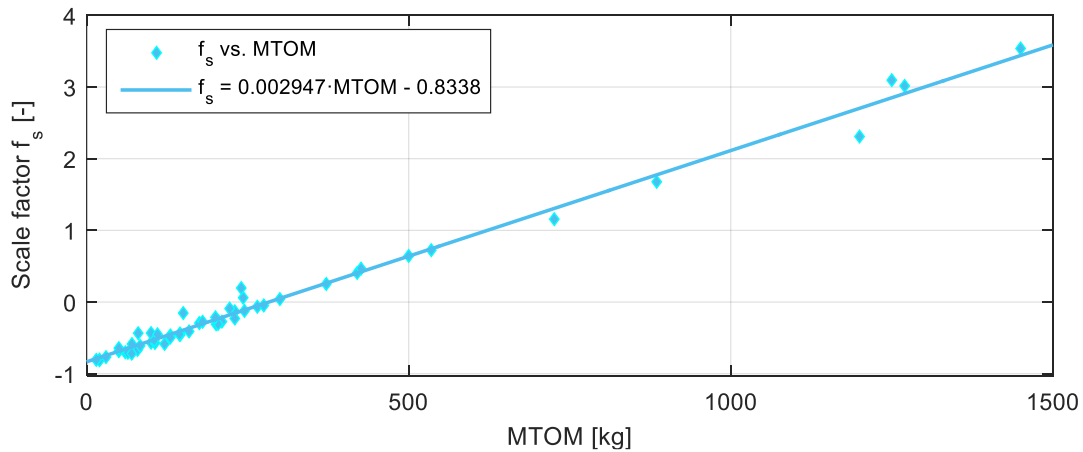


Figure 7-32. Linear regression Scale Factor – MTOM for the $n = 53$ RPA remaining in the data matrix of this application case. $R^2 = 0.989$, $RMSE = 0.1072$.

This regression shows reliable statistical parameters, as seen in the values of the coefficient of determination and standard error. Therefore, this correlation could be used in the proposed RPA conceptual design method as a starting point in order to estimate the value of the common factor from an initial value of $MTOM$. Then, upon having estimated the value of f_s , and since the coefficients of the factor loading matrix, A_{vxq} , are known, the values of the other observable design variables may be obtained. This idea shall be developed thoroughly in subsection 7.6.2.

(b) Aerodynamic surface design variable study

The second of the application cases is focused on variables which define the size and relative locations among the different aerodynamic surfaces. In the case of the H-tail configuration of RPA, these elements would be the wing, the HTP, and the twin VTPs. The main challenge with this application case is the low amount of data which is available in the literature for the parameters associated with the tail surfaces, as it was seen in Table 7-3. Since a complete data matrix is required to obtain the correlation matrix and then to continue on to the following steps of factor analysis, including this tail variables in the study will effectively restrict the sample to those RPA for which the values of the tail surface variables are known. The consequence of this is a reduction in the sample size, so the different methods which were proposed in subsection 7.4.3 in order to verify the statistical significance of the results and the possibility of population inference shall be more relevant here.

The features selected for this study are the following:

- **Variables:** wingspan, b_w , Maximum Take-Off Mass, $MTOM$, Payload, PL , wing surface, S_w , HTP surface, S_h , HTP moment arm, L_h , total surface of VTPs, S_v , and endurance, E .

- **Resulting data matrix sample size: 18 RPA.**

In this case, the selection of the variables has had to be done with more care. This is due to the nearby values of the sample size and the observable variables, with their difference as commented beforehand producing a decrease in the F-value of the corresponding test and in the population $\widetilde{R}^2$. Therefore, a similar representation to that which was used in Figure 7-28 to analyse the impact of the number of variables and the original coefficient of determination shall be employed here to substantiate the selection of the characteristics to be studied while observing the statistical aspects. This is shown in Figure 7-33.

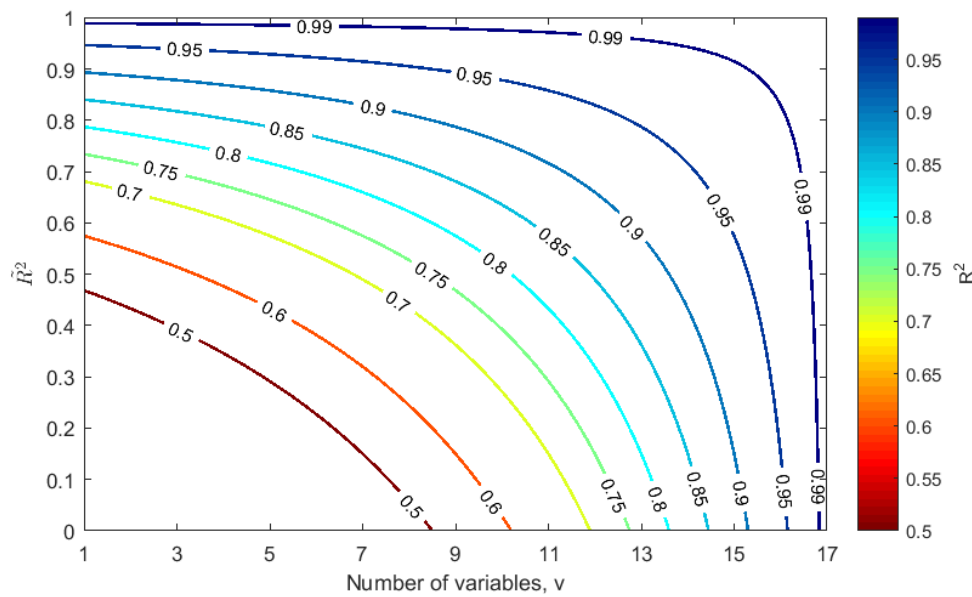


Figure 7-33. Representation of the population $\widetilde{R}^2$ versus the number of variables considered in the factor analysis study v and the original R^2 for a sample size n of 18 RPA.

In the current study, the effect of the population correction can be expected to be more severe. If the eight variables proposed beforehand are kept, then this scenario would be represented in the former figure by a vertical line in the coordinate $v = 8$. It can be seen that, should the relationship between both variables have a starting value of R^2 of 0.5, the population correction would yield a negligible relationship. Even for a starting value of R^2 of 0.6, the coefficient of determination would be halved by the population correction. Therefore, in order to be able to include all of the proposed variables, which will be essential to include an initial estimation of the tail planes in the geometric sizing method to be obtained from these results, the original sample values of R^2 must be considerably high, so that the population correction does not severely reduce them.

The mass variables *MTOM* and *PL* have been maintained in the case that they can constitute starting points for the geometric sizing process, so long as the factor measurement coefficients permit this. Furthermore, the *MTOM* has been shown through

the regressions of 7.6 to have a strong relationship with S_w , and from this latter variable the remaining aerodynamic surfaces were sized, so including this mass variable here is also supported by its proven correlation with other feature associated with the aerodynamic surfaces. Both $MTOM$ and S_w have been used in previous manned aircraft studies for the sizing of the tail surfaces (7; 42), supporting their consideration among the variables taken into account here. The endurance has also been included as a performance parameter in the case that the factor measurement coefficients allow to employ it as a starting point for the sizing process conceptual design method to be proposed in subsection 7.7.2. Furthermore, it is also related to size and mass variables through the span loading, as already described in 7.6.2. The remaining variables are related to the tail surfaces and are thus focal to the study conducted here, since it seeks to fill in the gap in the state-of-the-art in relation to the initial sizing of these elements.

In the same way as the previous section, the first step consists in obtaining the correlation matrix of the observable variables, which is shown in Table 7-10.

Table 7-10. Correlation matrix for the aerodynamic surface design variables.

	b_w	$MTOM$	PL	S_w	S_h	L_h	S_v	E
b_w	1	0.955	0.973	0.981	0.952	0.930	0.957	0.848
$MTOM$	0.955	1	0.990	0.975	0.966	0.945	0.958	0.808
PL	0.973	0.990	1	0.975	0.954	0.929	0.956	0.822
S_w	0.981	0.975	0.975	1	0.985	0.968	0.984	0.813
S_h	0.952	0.966	0.954	0.985	1	0.970	0.977	0.759
L_h	0.930	0.945	0.929	0.968	0.970	1	0.966	0.727
S_v	0.957	0.958	0.956	0.984	0.977	0.966	1	0.744
E	0.848	0.808	0.822	0.813	0.759	0.727	0.744	1

The analysis of the results presented in the correlation matrix shall focus on those interrelationships with a clearer physical meaning. This is due to two variables being able to present a high correlation even though there are no direct physical phenomena, as this could be due to a third variable that correlates significantly with those two, and which is the one that holds the physical interpretation (378). This can be seen, for instance, in the case of the high correlation between S_h and $MTOM$, which is most probably caused by the notable interrelationship of both of them with S_w , in which case $S_w - MTOM$ and $S_h - S_w$, as it was seen in 7.6.2, are the regressions which would hold a physical interpretation.

The physical interpretation of the regressions of $MTOM$ with the wingspan, PL , and the endurance were expounded in the previous application case. It is noted that the correlation values have changed with respect to those of the corresponding Table 7-7 due to the modification in the data matrix, as the one here has noticeably fewer RPA. The high correlation between $MTOM$ and S_w is a classical trend of aircraft conceptual design, as commented in 7.6.2 where a regression of this kind was derived for the database RPA. Amongst the correlation coefficients of S_h , the one which corresponds to the wing surface

stands out, with a value of 0.981. This is also in line with the good results of the corresponding regression in the previous section. Furthermore, the interrelation of S_w , l_h and S_h can be associated with the HTP volume coefficient, V_h , which is also one of the main parameters employed for the sizing and location of the HTP (9; 83; 128). With respect to the VTP surface, S_v , it also shows high correlations with many of the other observable variables, increasing along with the general scale of the aircraft, and being related to the VTP volume coefficient, V_v , which was also studied in the preceding section.

With respect to the other correlations, it can be considered that they are mainly a consequence of the ones that have been expounded on above. Overall, save for the endurance, it can be seen that the observable variables are very strongly correlated, as only a few coefficients fall below 0.9. Furthermore, it can be seen that the interrelationships among many of these variables can be based in their interpretation within the field of aircraft design.

The next step consists in estimating the communalities of each of the observable variables. The results corresponding to the present application case are shown in Table 7-11.

Table 7-11. Population inference statistical parameters for the study of aerodynamic surface design variables.

Value	p-value	R^2	$\tilde{R}^2$
b_w	$6.55 \cdot 10^{-8}$	0.982	0.969
$MTOM$	$2.14 \cdot 10^{-9}$	0.991	0.985
PL	$1.18 \cdot 10^{-9}$	0.992	0.986
S_w	$1.90 \cdot 10^{-10}$	0.994	0.990
S_h	$6.15 \cdot 10^{-8}$	0.982	0.970
L_h	$4.00 \cdot 10^{-6}$	0.958	0.929
S_v	$2.08 \cdot 10^{-7}$	0.977	0.961
E	$3.19 \cdot 10^{-3}$	0.833	0.715

Understandably, due to the lower sample size when compared to the previous case study, the p-values are in this case higher, but all of them still fall within the acceptable margin established by the 5 % level of significance employed in this study. Therefore, it can be deduced that the population regression is statistically significant, and thus the population correction can be applied. Even though the values of $\tilde{R}^2$ can fall severely when the number of variables is close to the sample size, as seen in Figure 7-33, in this case the high values of the sample R^2 allow to obtain adequate values of the population coefficient of determination. This shows that a strong interrelationship amongst the original values can achieve valid results in factor analysis even though the sample size falls within the interval of possible issues as stated by other authors (371; 393; 394). In this case, the communality estimates are, save for the endurance, all higher than 0.9. Previous references consider the a communality value of 0.8 as satisfactory, aiding to substantiate the validity of the results obtained here. This is also, to a certain degree, to be expected in this area of aircraft

design which is being studied, where higher interrelationships among its variables when compared to other disciplines can be anticipated due to the strong physical phenomena and design trends which link the features studied here (372).

The high values of the estimated communalities allow to foresee that the factor solution will also be representative of the population in spite of the lower sample size, since these values are also appreciably higher than those of the global design variables study conducted previously. Therefore, even though the sample size is comparatively low when compared to the previous case of study, the strong values obtained for the statistical indicators augment the confidence in the results.

The next step in the factor analytic process consists in obtaining the values of the A_{vxq} and D_{vv} arrays. As in the previous case study, the classical scree analysis (386; 387) shall be compared with the new method proposed in this thesis that consists in analysing the factor loadings as Pearson linear correlation coefficients for their statistical significance.

The scree plot corresponding to the present case of study is similar to the one shown for the global variables design in Figure 7-29. Once again, the solution of the scree analysis suggests that only one common factor is retained. This result will be compared with the method proposed in this thesis taking into account the statistical meaning of the A_{vxq} matrix coefficients. An idea that must be highlighted at this point is that the coefficients of the common factors, when applying the same extraction methods, are dependent of the correlation matrix, but not of the sample size (383). The method proposed in this thesis takes into consideration this latter parameter in determining the significance of the factors. Therefore, for scenarios in which the population inference is not as evident, such as the present case of study, it can be considered a more robust approach to the selection of the factors to retain.

In this case, when solving the Lagrange Multipliers problem for the PF Method, the results indicate that only one factor can be extracted. Once again, a Heywood Case prevents the second factor to be kept. The coefficients of the A_{vxq} matrix corresponding to the extraction of one common factor according to the proposed method can be seen in the first two columns of Table 7-12. As in the case of the first application case, the p-values associated with the coefficients of the factor fall within the level of significance in spite of the low sample size here. This satisfactory behaviour can also be checked with the cutoff value for the statistical significance of the Pearson correlation coefficient of 0.4683, shown in the caption of the table.

Table 7-12. Coefficients of the factor pattern matrix associated with the extraction of one factor for the aerodynamic surface design variables application case, accompanied by their corresponding p-values analysed as Pearson linear correlation coefficients. Results are shown for both the PF and Minres methods. The cutoff value for the coefficient for a sample size of $n = 18$ is of $r = 0.4683$ in order to guarantee statistical significance.

Variable	Factor 1 (PF)	Factor 1 (PF) p-value	Factor 1 (Minres)	Factor 1 (Minres) p-value
b_w	0.983	$2.68 \cdot 10^{-13}$	0.984	$1.96 \cdot 10^{-13}$
$MTOM$	0.986	$5.43 \cdot 10^{-14}$	0.985	$9.62 \cdot 10^{-14}$
PL	0.987	$5.04 \cdot 10^{-14}$	0.985	$1.05 \cdot 10^{-13}$
S_w	0.998	$2.55 \cdot 10^{-21}$	~ 1.000	$1.62 \cdot 10^{-41}$
S_h	0.981	$7.36 \cdot 10^{-13}$	0.981	$7.72 \cdot 10^{-13}$
L_h	0.959	$3.21 \cdot 10^{-10}$	0.959	$3.47 \cdot 10^{-10}$
S_v	0.978	$3.02 \cdot 10^{-12}$	0.978	$2.88 \cdot 10^{-12}$
E	0.811	$4.52 \cdot 10^{-5}$	0.804	$5.89 \cdot 10^{-5}$

It is highlighted that the factor has a remarkably strong correlation with the observable variable corresponding to the wing surface. Furthermore, it also shows a notable relationship with the size of the other aerodynamic surfaces, with these being the HTP and VTP. In the area of aircraft conceptual design, regressions amongst these variables are common in the sizing of the tail surfaces (7; 42), as it has also been done in the previous regression study within this thesis. This supports the fact that the underlying factor represents the overall magnitude of the aerodynamic surfaces of the RPA, fitting with the topic of the application case conducted here, which is focused on aerodynamic surface design. It is seen that all surfaces would be enlarged along with the rise in the latent factor, which is consistent with the positive correlations among these variables as seen in section 7.6.

There is also a strong correlation of the factor with $MTOM$, which is also associated with S_w through to the wing loading design parameter. The high correlation with the wingspan can also be related to the wing sizing of the aircraft (392). The case of S_v should be highlighted, since a sufficiently satisfactory regression was not found for this variable in the research conducted within the previous section. However, in this case, when accounting simultaneously for all interactions among the variables, a factor has been extracted which correlated remarkably well with this variable, which will allow to perform its sizing through a method different to the one based on volume coefficients which was used beforehand.

In view of the above, the fact that the highest correlation of the factor is with S_w could be attributed due to this variable being the central node between the aircraft overall mass with the size of the remaining aerodynamic surfaces, which is a behaviour also seen in the geometric sizing process extracted in the preceding section and seen in Figure 7-26. This reinforces the point that the wing sizing is the main aspect to consider when interpreting

the physical meaning of the underlying trend represented by this factor. This aerodynamic surface factor shall be noted hereafter as f_a .

The next step consists in applying the minimum residuals approach for factor extraction, following the same process as before. Its results are shown in the last two columns of Table 7-12. Here it is seen that there is a nearly complete correlation between the factor and the wing surface, further reinforcing their connection. Again, the factor is significant from a statistical viewpoint considering the parameters for this study. With this, and focusing on the results from this latter factor extraction method, the communality and uniqueness of each variable can be obtained, which are shown in the top graph of Figure 7-34, with the one below representing the relative difference in factor loadings between both factor extraction approaches, which is again remarkably low.

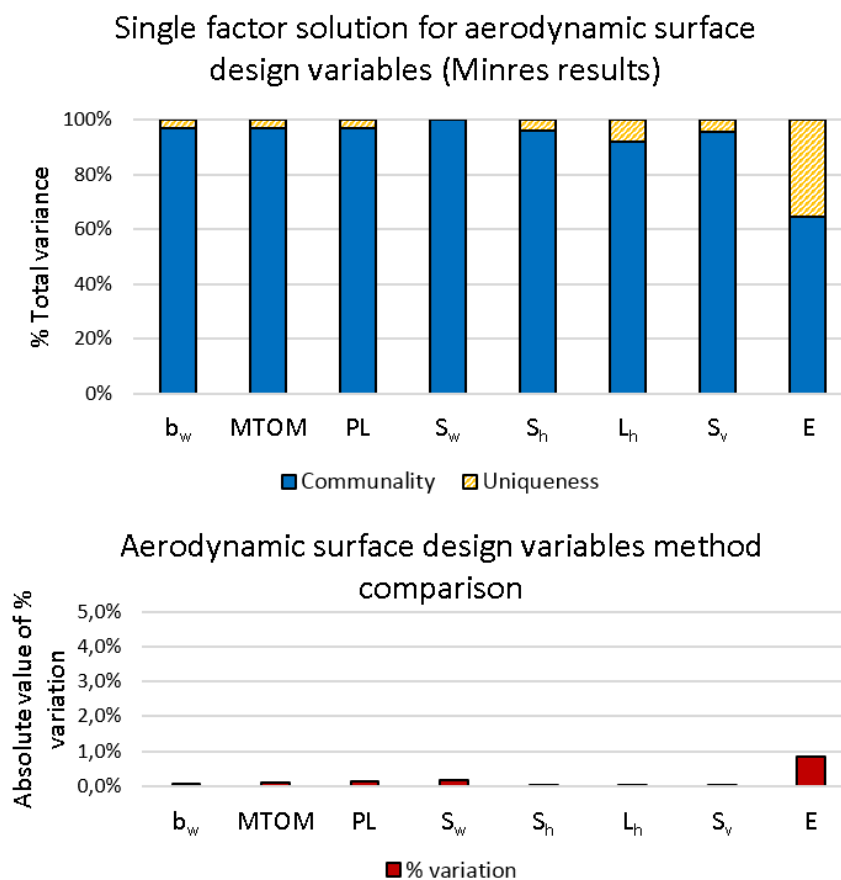


Figure 7-34. For the aerodynamic surface design variable case, the graph above represents the variance accounted for by the common factor which is shared amongst all variables (communality) and the variance related to the specific factor particular to each of them (uniqueness). The graph below shows the percentage difference in absolute value between the application of the PF and Minres methods for factor extraction, calculated for each common factor loading.

In view of Figure 7-34, the results of the aerodynamic surface variable study are even more promising towards deriving a geometric sizing approach. This is due to the common factor accounting for more than 95 % of the variance for all observable variables except

for L_h , where it still is above 90 %, and also for the endurance. Therefore, if the value of the common factor is known for a new RPA to be designed, the observable variables could be estimated with errors potentially below 10 %. Therefore, the results can be considered valid in order to develop the geometric sizing method for RPA that is the focus of this study, and which seeks to enable the preliminary sizing of the tail surfaces at the initial design steps. With respect to the differences between the results of both extraction methods, these are even lower than for the global variables, further supporting the validity of the results.

Therefore, in order to leverage this common factor, which can be invaluable for the sizing of the aerodynamic surfaces in the proposed conceptual design method for RPA, a method for estimating it must be proposed. As in the case of the previous application scenario, this will be done through the factor measurement step, obtaining the coefficients of the multiple linear regression of the common factor as estimated by the observable variables, which are represented in Figure 7-35.

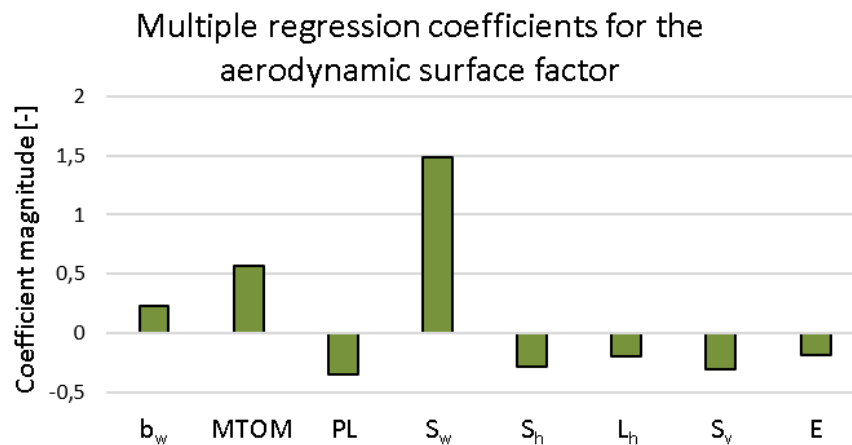


Figure 7-35. Multiple linear regression coefficients of the correlation to estimate the RPA aerodynamic surface factor f_a as a function of the observable variables for the aerodynamic surface design variables application case.

As it can be seen, the scenario has changed remarkably with respect to the previous case. Here, the strongest correlation is with S_w , which is consistent with the observed factor loadings and the tight link of this f_a factor to the wing surface area. However, it should be taken into account that the main use for these statistical results is to propose a way to estimate the common factor from some observable variables which can be employed as initial steps of the sizing process. From this viewpoint, the wing surface would not a variable which can be used, at least on its own, as a starting point of the workflow of RPA sizing. Moving on to the second highest regression, this is the one with $MTOM$, which was also strongly correlated to the underlying factor. This observable variable could be used as the starting point of the sizing process in the same vein as it was proposed for the basic

study in the correlation case. However, the multiple correlation coefficient corresponding to it is not as large as that of S_w . Then, the coefficients for the remaining variables are much lower.

In view of this, it is proposed to use $MTOM$ alongside S_w as the variables from which the factor will be estimated. These two variables are related to the wing loading design parameter, and one of them, $MTOM$, is consistent with its use as the input of the design workflow. To estimate the other variable, S_w , before moving on to employ them both to obtain the common factor, it is proposed to use the $S_w - MTOM$ correlation which was obtained in the previous section, as seen in Figure 7-14. Then, the common factor is estimated through a multiple linear regression calculated between S_w and $MTOM$ with f_a for the RPA in the data matrix of this application case. No other observable variables are used at this step since their coefficients as seen in Figure 7-35 are much lower than those for S_w and $MTOM$, and they would be less aligned with their use in the initial steps of design. With the proposed path, the proven relationship of both of these variables as predictors of the common factor is not neglected, and at the same time, a starting point which is reasonable for the workflow of geometric sizing has been given.

As in the previous application case, it is seen that the variables which could be more aligned with initial specifications, PL and E , have not shown strong correlations with the factor at the measurement stage. Therefore, even though they were included in the model with one of the purposes of this being in case that they could be used at the end of the process as starting points of the workflow, this is not possible due to their comparatively weak coefficients when estimating the factor itself through a multiple linear regression.

Now, in a similar manner to the $f_s - MTOM$ regression of the previous application case, here, the aforementioned multiple regression to estimate f_a using both S_w and $MTOM$ as predictors is now obtained from the database RPA. The resulting expression is shown in the following equation:

$$f_a = 4.813 \cdot 10^{-4} MTOM + 0.1893 S_w - 1.156 \quad [7-49]$$

where it is noted that the low value of the coefficient associated to $MTOM$ occurs since this variable has been included in true magnitude for the estimation of the regression. A graphical representation illustrating this multiple regression can be seen in Figure 7-36. In view of the reliable statistical parameters obtained for this regression, it can be proposed for the estimation of the common factor which can then be used in the RPA conceptual design method that will be expounded on in the next subsection.

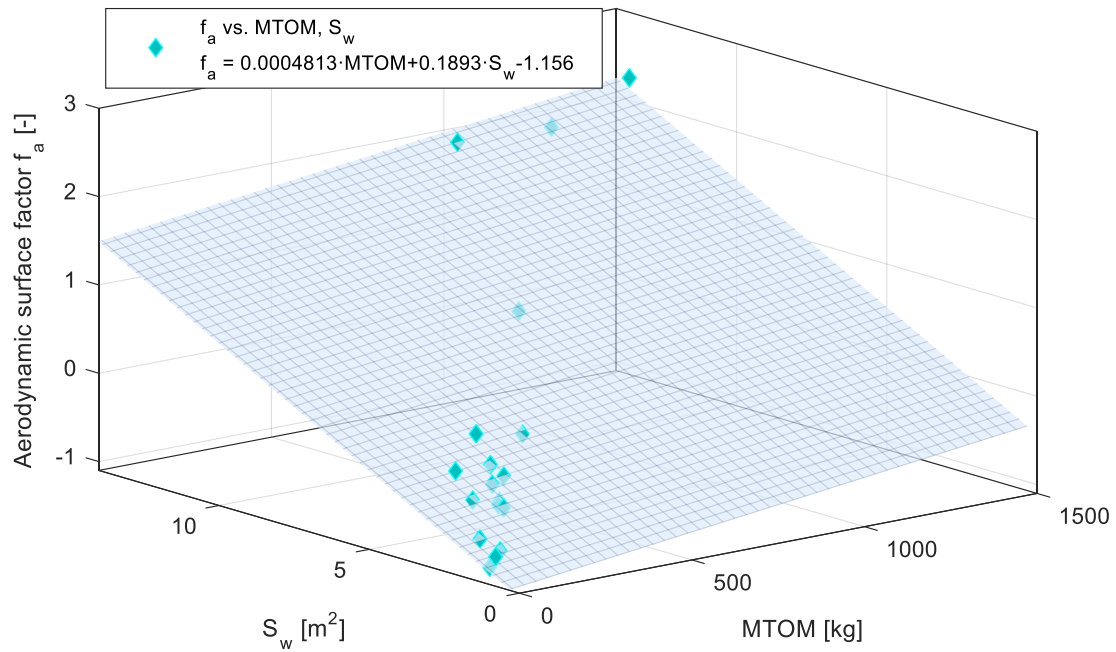


Figure 7-36. Multiple linear regression of Aerodynamic Surface Factor – $[MTOM, S_w]$ for the $n = 18$ RPA remaining in the data matrix of this application case. $\widehat{R}^2 = 0.9915$, $RMSE = 0.0929$.

(c) Overall remarks of factor analysis application

At this point, the application of the factor analysis process itself would be finished. Aside from its use to derive a new geometric sizing method in the following subsection, it has been seen that relevant insights have already been obtained from the design trends of the RPA included in the sub-dataset through these two application cases. The analysis of the regression matrices between the observable variables along with the physical interpretation of the latent factors has revealed that most RPA in this sub-dataset of reciprocating engines and H-tail seem to follow a certain scale effect, both in terms of general variables, as well as in the size of the aerodynamic surfaces. This way, it can be said that different RPA of this category show a general similarity to each other, with the main differences being an overall increment or decrease in their size. The cruise speed and endurance variables are the only ones which do not appear to follow this trend as closely as the others.

The issues regarding data scarcity that were anticipated in 7.5 have influenced the analysis of the results. It is seen that adding some variables of the tail surfaces results in a sample reduction of the data matrix to around a third of the one of the general variable study. Even for the first application case of the general variables, it is relatively common that an aircraft of the sub-dataset is missing at least one of the seven variables considered therein. Therefore, especially in the second application case, the use of the statistical inference verifications and population corrections have been essential to support the validity of the results.

7.7.2. Conceptual design method for H-Tail RPA based on factor analysis

In view of the results obtained with the factor analytic process of the previous section, it can be seen that this methodology has demonstrated its usefulness in detecting the latent design trends of RPA. The expressions and results which have been obtained are satisfactory both from the viewpoint of their interpretation according to aircraft conceptual design criteria, as well as from a statistical standpoint regarding their tests and metrics.

Therefore, the next step will consist in employing these results as a means of elaborating a geometric sizing procedure of RPA based on the design trends which have been identified in the previous section and employing the factor analysis equations. Both application cases on the global and aerodynamic surface design variables shall be employed.

As seen in the roadmap of Figure 7-6, from some initial variables which may be known for the new RPA to be designed, firstly the values of each of the two common factors are estimated for the new aircraft. As commented through the previous subsection, and in a similar vein to what was done in the regression-based approach, the value of *MTOM* is considered as the initial point of the workflow, with the same considerations as the ones discussed at that point. The use of the $S_w - MTOM$ regression of the preceding section allows to obtain the wing surface, and with these two variables, the regressions shown in Figure 7-32 and Figure 7-36 can be used to obtain the values of the underlying factors.

The following step is the use of the factor analysis linear model equations, corresponding to [7-33], to estimate the rest of the observable variables from the common factors. At this step, if a large amount of variance of the first ones is mostly expressed through the underlying factors, it can be expected that the accuracy of the model will increase, as the value which has already been obtained for the factors can serve to express with satisfactory accuracy the changes in the observable variables. Thereby, from the analysis of the communality and uniqueness proportions in each application case, the focus has been on those variables for which more than 80 % of their variance is explained by the common factor. If a variable appears in both cases, the one with a higher communality and physical interpretation of the variable in relation to the factor has been prioritised. Finally, albeit the common factor only account for 60 % of the variance associated to the endurance, this variable has also been included for use as a check on the initial specification as it will be commented shortly ahead. The following list provides the variables which will be obtained through each factor:

- **Scale factor (f_s):** length, l , Payload, PL , and engine power, P_E .
- **Aerodynamic surface factor (f_a):** wingspan, b_w , HTP surface, S_h , HTP moment arm, L_h , and total surface of VTPs, S_v , and endurance, E .

One of the highlights of the proposed geometric sizing approach is the use of the common factors, which represent underlying design tendencies for the sample of RPA, as a sort of specifications within the conceptual design phase. Albeit they are obtained as an intermediate step as a function of observable variables which are more tangible for the designer, the fact that the rest of the variables of interest are obtained directly from the factor emphasises that the focus of the sizing approach is on the influence of the underlying trends on the observable characteristics, with this being one of the original aspects of the proposed methodology.

As mentioned beforehand through this section, the usual design process would involve using the payload, PL , and endurance, E , as an initial specifications. However, since the factor analytic results have not enabled to use them as predictors of the common factors, an alternative approach is suggested here to keep a certain influence of these requirements in the geometric sizing process in a compatible way with the expressions that have been obtained. The designer will establish in advance desired intervals for these variables which represent a set of payload and endurance values for common missions envisioned for the future RPA. Then, from the corresponding factor, the values of these characteristics are estimated as related to the underlying design trends represented by the factors. These estimated values are checked against the intervals set as specifications to check whether the desired payload and endurance intervals for the aircraft fall within the values given by the design trends represented by the factors, which can be used as a means to validate the results of using the factor analysis approach.

This kind of approach of obtaining an endurance from statistical estimations instead of setting it as an initial requirement itself, and then using it to check with the requirements, has also been done in previous research within the field of statistical estimations for RPA (46). Furthermore, in other areas, the approach of estimating payload and endurance within the results of the conceptual design process as a function of other parameters has also been employed (120). In this case, however, taking into account that the communality for the endurance was much lower than the others, the verification proposed here should not be considered definitive. This is one of the reasons for the development in chapter 9 of a performance-based approach which does start from the initial mission requirements and validates the compliance of the aircraft with them through a physics-based approach, thus complementing these statistical methods.

Some other comments are given here regarding the sizing process. In this case, as the VTP moment arm has not been included in the set of variables, and thus a mathematical relationship for estimating it is not available, as a first approximation it will be considered approximately equal to the one of the HTP. Regarding the length of fuselage, l_f , and tail booms, l_b , as in the case of the regression-based method, these can be obtained from the overall length and the use of typical values for the quotients l_f/l and l_b/l as seen in similar aircraft to the one which is being designed. Additionally, as in the previous section, it is highlighted that the wing obtained from this sizing process is a straight-tapered one, as it

has been obtained from the equivalent wings of the RPA of the database, with the designer being able to shape it into more complex shapes while observing the applicable geometric constraints if desired.

To obtain the observable variables from the two different factors, the equations of the factor analysis lineal model [7-33] are used, employing as factor loadings the ones obtained through each of the application cases. This allows to define the observable variables as a function of both common and specific factors. By using the results of Table 7-9 and Table 7-12, the corresponding loadings are introduced in the system of equations, prioritising the ones obtained with the Minres approach. The expressions corresponding to the global design variables case are shown below:

$$l' = 0.929 f_s + 0.369 e_l \quad [7-50]$$

$$PL' = 0.941 f_s + 0.338 e_{PL} \quad [7-51]$$

$$P'_E = 0.899 f_s + 0.439 e_p \quad [7-52]$$

where these would be the variables sized according to the scale factor, which in turn is estimated according to the regression seen in Figure 7-32. It must also be stated that the apostrophe ' refers to the variables corrected with the sample mean and standardised with the corresponding standard deviation.

The following expressions correspond to the aerodynamic surface design variables case:

$$b'_w = 0.984 f_a + 0.178 e_b \quad [7-53]$$

$$S'_h = 0.981 f_a + 0.194 e_{S_h} \quad [7-54]$$

$$L'_h = 0.959 f_a + 0.283 e_{L_h} \quad [7-55]$$

$$S'_v = 0.978 f_a + 0.210 e_{S_v} \quad [7-56]$$

$$E' = 0.804 f_a + 0.595 e_E \quad [7-57]$$

where the above variables would be sized with the aerodynamic surface factor, which itself is estimated according to the multiple linear regression shown in equation [7-49].

One last issue that must be addressed before the above expressions may be employed, which relates to the specific factors of each variable. As mentioned in the factor analysis theoretical background, these factor neither correlate among them nor with the common factors. Thereby, whereas estimating the common factor for the new RPA has been possible, such a procedure for the specific ones, of which there are one per variable, would not be feasible. However, as seen through the factor analysis solution for both application cases, the uniqueness associated to each variable, which is the part of its variance that is accounted for by the specific factor, is usually remarkably low when compared to the communality. Since in most cases this specific factor represents less than 10 % of the variance, it can be considered that discarding their contribution can fall within the acceptable margin of error of conceptual design, and it allows to close the system of equations to establish the geometric sizing approach.

In essence, the hypothesis mentioned above can be considered analogous to the one employed when estimating a new point through a regression model, where the residual term associated to the scatter of the points is usually discarded as a first approximation when predicting new responses. This has been applied through different aircraft design methodologies based on regression models (8; 42).

Finally, in order to obtain the value of each observable variable in real magnitude, it must be multiplied by the corresponding standard deviation and then adding to this result the mean of the RPA sample extracted from the corresponding data matrix. With this, the system of equations that give the observable variables in a closed form as a function of the common factors is provided below:

$$l [m] = (1.811 \cdot 0.929 \cdot f_s) + 4.382 \quad [7-58]$$

$$l_f[m] = l \cdot \left(\frac{l_f}{l} \right) \quad [7-59]$$

$$l_b[m] = l \cdot \left(\frac{l_b}{l} \right) \quad [7-60]$$

$$PL [kg] = (79.96 \cdot 0.941 \cdot f_s) + 57.09 \quad [7-61]$$

$$P_E[kW] = (32.81 \cdot 0.899 \cdot f_s) + 33.62 \quad [7-62]$$

$$b_w[m] = (4.44 \cdot 0.984 \cdot f_a) + 7.51 \quad [7-63]$$

$$S_h[m^2] = (0.717 \cdot 0.981 \cdot f_a) + 0.926 \quad [7-64]$$

$$L_v[m] \cong L_h[m] = (1.19 \cdot 0.959 \cdot f_a) + 2.56 \quad [7-65]$$

$$S_v[m^2] = (0.457 \cdot 0.978 \cdot f_a) + 0.671 \quad [7-66]$$

$$E[h] = (13.16 \cdot 0.804 \cdot f_a) + 12.69 \quad [7-67]$$

With these steps the design process for RPA based on factor analysis would be concluded. It can be seen that the mathematical and workflow schema of this approach is starkly different to the one based on regressions of 7.6.3. In the case shown here, the number of consecutive expressions until a final value is reached for each variable is much lower. This is due to the centralised nature of the factor analysis approach, where upon defining the common factor, all remainder variables stem directly from it, as illustrated in Figure 7-5 when expounding the main concept behind this method. Therefore, the reduced number of intermediate steps may result in reducing the error couplings which were mentioned in 7.6.4, which can be expected to be more noteworthy in a sequential process as it was the case of the regression approach.

7.7.3. Factor analysis method case study

The following step in order to validate this model shall be to apply it to the design of an RPA which has not been included in the database and compare the values of the different observable variables obtained with the method and the ones that correspond to the existing RPA.

The RPA selected to test the sizing method is the RQ-2 Pioneer, which is the same RPA used for the H-tail correlation case in 7.6.4. The starting value for the design process is the aircraft *MTOM*, which is of 205 kg as mentioned previously. However, in this case, as commented in the previous subsection, ranges for typical payload and endurance values are also given so as to check the values for these variables obtained through the factor analysis against the initial specifications. Payload values for this RPA have been found from 30 kg to 45 kg, and for the endurance, values have been found ranging from 5.5 h to 8 h (32; 395). The results obtained following the factor analysis sizing approach proposed in this thesis are compared with the actual values of the RPA, and the relative error between both is shown in Table 7-13.

Table 7-13. Case study of the geometry sizing process based on factor analysis for the RQ-2 Pioneer.

Variable	Units	Real Value	Estimated Value	Relative Error
I	[m]	4.370	4.000	-8.6 %
I_f	[m]	2.900	2.52	-13.1 %
I_b	[m]	2.210	2.00	-9.5 %
PL	[kg]	[30-45]	39.81	-
P_E	[kW]	28.3	26.85	-5.1 %
S_w	[m ²]	3.181	3.182	0.02 %
b_w	[m]	5.130	5.524	7.7 %
S_h	[m ²]	0.591	0.606	2.5 %
L_h	[m]	2.20	2.047	-7.0 %
S_v	[m ²]	0.50	0.468	-6.5 %
E	[h]	[5.5-8]	7.88	-

In view of the estimated results, these fit the actual values of the RPA within the margin of error of conceptual design, and overall the application of the factor analysis give as a result a geometric sizing of the aircraft similar to the existing one. The fact that these relative errors are usually below 10 % was already advanced in the analysis of the variance accounted for the common factors, where it was seen that in most cases the communality was above 90 %. This allows the factors to predict the observable variables with a good accuracy, since the portion of their variance which is not accounted for by the common factors is comparatively low. These satisfactory results support the validation of the proposed geometry sizing method for H-tail RPA, also sustaining this original approach based on the use of latent design trends, as well as the use of factor analysis in the conceptual design of aircraft, which is a novel area of application for this statistical methodology.

Finally, since the previous section conducted a similar case study on this RPA but employing the regression-based approach, a comparison between the error of both approaches when contrasting the value of the variable with the actual one of the RPA is shown in Figure 7-37.

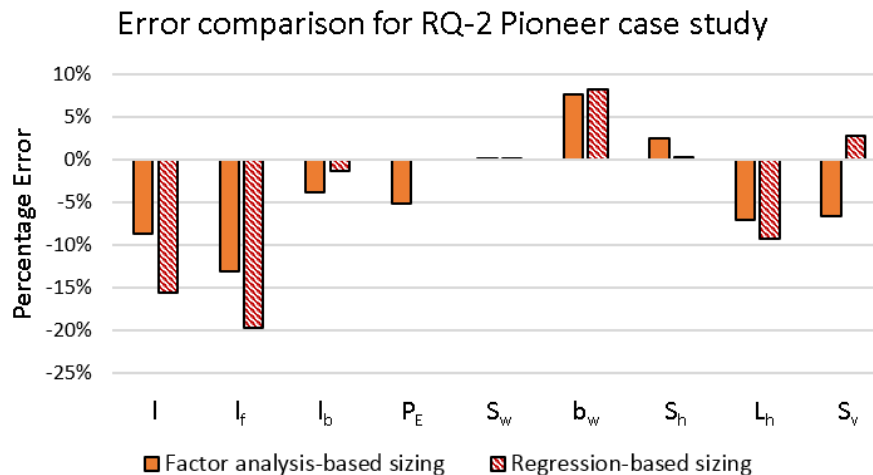


Figure 7-37. Comparison between the errors in the estimation of the different variables for the RQ-2 Pioneer RPA employing both approaches developed in this chapter of the thesis. The variable P_E was not available in the regression method.

As it can be seen, the percentage error of both methodologies is comparable, and they both fall in most cases within the acceptable margin in conceptual design. However, the error of the factor analysis method seems to be more evened out across the different variables, whereas the one from the regression model shows more abrupt changes between different variables, with S_h having a reduced error when compared to that of factor analysis, and in contrast, for l the error is nearly doubled in the regression case. In this regard, it must be considered that the regression sizing method is largely sequential, and as it was discussed when presenting its case study, this can give rise to certain couplings between the errors, which can lead to amplifications or in some cases reductions caused by the interactions among the errors of the preceding variables. In the factor analysis approach, at most there are three steps between the starting point and the calculation of the final variables, since the schema of the sizing method is more centralised around the factors. Another aspect which may explain this behaviour is that the sizing equations ensuing from the factor analysis approach account for all simultaneous variance interactions between the different features, which may also lead to the differences to be more evened out. A more detailed analysis on the ways in which the error coupling behaves between both methodologies would constitute an avenue of future work to study in more detail how the calculation process affects the propagation and interaction of errors.

The largest reduction in errors can be seen in the case of the variables associated to the lengths. This may be due to the fact that the correlation of $l - L_{tail}$ was among the ones with more scatter as seen in the previous section. Even if in the factor analysis approach the variable l has a communality which is somewhat lower to the others, being close to 80 %, the result is still more satisfactory than that achieved through the regressions. It is noted that in the case of regression analysis a satisfactory regression was not found for the

engine power, but here this variable achieves good results both in communality and in the case study. Once again, this can be attributed to the multivariate approach in itself, which allows to capture combined interactions to explain the variance affecting this variable, thus allowing the predictor factor to more accurately estimate it.

7.8. Summary and conclusions

In view of the growth of RPAS, the development of rapid-sizing conceptual design tools focused specifically on this type of aircraft to aid in the initial phases of their design is becoming increasingly demanded. This can be seen in the number of previous research within the topical area of statistical approaches for RPA design, as this is a field with great potential to develop empirical methodologies with low computational cost that can be used in the first stages of RPA development.

In spite of the recent growth of research in this realm along with it being one of the topical areas with most amount of works as already seen in chapter 2, there are some specific gaps which remain to be covered by previous works. These mainly comprise the estimation of trends with respect to variables such as those related to the tail surfaces, fuselage, and tail boom. This can be explained as they are characteristics for which data is seldom found within the literature. In spite of this, the main purpose of the work conducted in this chapter was to study these variables, which would be a remarkable asset for the development of overall initial sizing approaches covering the design of the elements of the aircraft related to these variables, which is a gap seen in the RPA conceptual design state-of-the-art from a broader perspective than just within statistical methods.

The compilation of the RPA database used in this chapter was one of the major lines of work during the doctoral studies. The overall trends which were extracted from the database in terms of categorical variables have allowed to quantify and consolidate some observations made beforehand along the thesis. These include the diversity of configurations shown by existing fixed-wing RPA, and also the misalignment between the layouts which are currently being studied by most design environments and the ones which are more widespread in RPA. Some of the trends which were extracted, such as the prevalence of each configuration and the wing planform type distributions, had not been analysed beforehand in other lines of research within the field of RPA statistical study, constituting novel findings of this research.

Two statistical approaches were investigated during this chapter, seeking to use each to derive a new geometric sizing workflow for a sub-dataset of RPA formed by categories with an acceptable volume of data. These two statistical methods comprise regression analysis and factor analysis. The first is a common procedure in previous works within this topical area, whereas the second constitutes a novel approach in this field, as this type of method had not been employed beforehand with a focus on aircraft of RPA design. As

seen both in the theoretical background and in the results obtained from the database analysis, some of the main characteristics and key points of each approach, and those of the design approaches derived from them, are summarised below:

- **Regression approach:** this methodology is much more tested and proven in the field of conceptual design. Since the correlations are usually estimated using pairs of values, this allows to more easily see the trends between the variables, and as the typical use of the variables in real magnitude leads to a more immediate interpretation of the results. Furthermore, when applying the method on distinct groups of two variables, this approach becomes more robust to missing data. This has been a key point to enable its use on configurations which had a lower number of data points, such as the conventional, T-tail, and V-tail layouts, as these could not be analysed with the multivariate factor analysis method due to the interactions among the missing data values. A key characteristics of the derived sizing method is that it is more hand-crafted and less systematic, with more degrees of freedom being present for decisions made by the designer. It must also be highlighted that the resulting design approach is mostly sequential, which is another consequence of the pairwise process of regression estimation, and this can lead at times to certain error couplings. Nevertheless, all obtained regressions showed satisfactory statistical metrics and the results from the case studies reveal that the error is within the acceptable margin of conceptual design.
- **Factor analysis:** since this is a multivariate method, it shows both advantages and challenges of this other type of statistical approaches. The data matrix is affected to a larger extent by missing data values, since now one aircraft must have data for all variables so that it can be kept in the dataset. This is one of the reasons which has limited its use to H-tail RPA. On the other hand, the approach reveals a larger number of dependencies not only between the observable variables themselves, but also along them with the factors extracted by the models. These factors serve to summarise all the information seen in the variance interactions among the characteristics included in the model, and they also reveal underlying trends in the data. On the other hand, the trends are more complex and are more difficult to see when compared to the regression approach. However, the latent patterns can be given a physical interpretation through the analysis of the correlations among the factor with the variables, revealing further insights on the design practices of RPA in the case of this study. However, due to the sample size issues, it is even more crucial in this case to perform all statistical tests and population corrections to confirm the possibility of inferring conclusions from the population. The resulting sizing approach is more systematic, requiring less intervention by the designer.

The main challenge to be surmounted in both cases was the low sample size due the data matrix reductions caused by missing data, particularly in the factor analysis approach. To

mitigate and watch over these issues, the statistical hypothesis tests and population correction aspects which were introduced in 7.3 were kept in mind through the analysis process. The large scatter present in some cases constituted another challenge. Previous authors have highlighted that this can be due to the fact that there are less systematic approaches currently available for RPA development, so many designers use ad-hoc procedures for each case (21; 105). This matter connects with the GDM and AADM types of design methods introduced in chapter 2.

The derivation of the geometric sizing approaches and their results have been satisfactory. These approaches are according to the nature of conceptual design methodologies, in that they constitute quick procedures to obtain initial values of the geometry and characteristics of the RPA. Albeit the analysis process has been complex, once the methodologies are established, whether by extracting and interpreting the factors in the factor analytic approach, or by establishing the different regressions and their sequence in the conventional method, the computational times are both negligible. This trait makes both of them suitable for the initial phase of conceptual design, in which the methodologies must be applicable in a short time, so as to make initial estimates which can then be compared and refined in further steps of the project. The accuracy achieved by both of them is according to the needs of the conceptual design stage, also fulfilling this aspect. Furthermore, the correlation method considers different configurations, thus advancing towards addressing one of the challenges mentioned in 1.3, which is that of the diversity of layouts of RPAS. The availability of new methods to perform the initial sizing of various layouts constitutes a noteworthy aid to the task of the designer of selecting and comparing various design alternatives. It is also highlighted that a number of regressions and histograms, mainly those related to the tail surfaces, fuselage, and booms, would constitute original contributions of this thesis, as similar results were not found in the state-of-the-art. The factor analytic approach and its adaptation to the realm of RPA design would also be considered novel approaches developed in this research. Thus, it can be considered that OBJ.3.1 of the thesis has been satisfied, with new design trends having been studied for RPA design, which have led to the derivation of the original geometric sizing methods proposed here.

Since the methods are mainly intended for the initial sizing step of the design process, as according to the thesis scope, they are mostly focused on variables which provide an overall definition of the aircraft and of its main airframe elements. This is usual in the conceptual design stage (41), where aspects such as a detailed provision of the fuselage OML or the distribution of wing twist and camber are not defined at this point, as these are typically left for future design steps either at the end of the conceptual phase or at the onset of the preliminary stage.

The research presented here has laid out the groundwork for future lines of work which can provide further advancements to the methods developed here. The coupling amongs the statistical error for each of the design workflows could be studied in more detail from

a statistical standpoint, to analyse their behaviour and its dependence with the steps of the methods in a more thorough manner. In view of the large scatter in endurance, particularly in the factor analysis approach, it can be deduced that perhaps RPA which have been developed at different points in time present dissimilar performance levels. This is an aspect already mentioned by previous authors (40; 105), and the first of these works even performed a classification of the RPA of the database used there with respect to the Entry in Service year. Considering the scope of the analysis conducted in this thesis, more data would probably be needed to perform this additional categorisation and retain an adequate statistical significance. Furthermore, other groupings could be studied to advance in further understanding their impact on RPA design trends, however in most cases this might also require a larger volume of data to compensate for the sample reduction due to simultaneous classifications. It can be expected that, if data for RPAS becomes more readily available in the future, the possibility of addressing these avenues of research will be improved.

Finally, as it has been noted when proposing the geometric sizing approaches based on both methodologies, these use as a starting point the value of MTOM of the new aircraft to be designed. However, in spite of the MTOM being a key design variable, it does not constitute an initial specification in a traditional sense, since these would mostly be variables which are related to mission performance such as the endurance, payload, and flight speed. This gap in the current methodologies shall be addressed in chapter 9, which develops a multi-role initial sizing method based on flight mechanics. This performance-based design approach will leverage as one of its main steps the geometric sizing methods employed here. This allow the value of MTOM to connect directly with the sizing based on integral performance, thus solving one of the areas of improvement of the approaches proposed here, and allowing to connect them to the initial specifications of the RPA project.

8. AIRWORTHINESS BASED APPROACHES FOR RPA CONCEPTUAL DESIGN

As seen in the overall literature review of section 2.2, and as also discussed within chapter 6, airworthiness-based design approaches are still relatively scarce in the domain of RPA. Furthermore, when considering the evolution of the regulations, many of the design approaches which have been developed previously might no longer be applicable to certifiable design cases. However, ensuring the compliance with applicable airworthiness criteria from the early design stages is fundamental towards the safety of the design and to ensure its adherence to the regulations which are in place. Thus, the aforementioned gap is among the ones with a potentially higher impact not only in the design methods themselves, but also in ensuring that the aircraft concept which is developed can then be deployed into practical use.

In view of this, the purpose of this chapter is to explore the development of airworthiness-based design approaches for the initial stages of RPA development. This matter is tightly interlinked with chapter 3, as airworthiness requirements firstly have to be extracted from the applicable regulations, with these having been reviewed in the aforementioned chapter while placing particular attention on documents which were more tightly related to the initial stages of design. Furthermore, several characteristics of the regulations related to airworthiness and design aspects were assessed, with some of them unveiling relevant hurdles towards their integration within design methods. This chapter seeks to tackle those challenges so as to enable a more straightforward development of design approaches incorporating RPA airworthiness requirements.

As it will be expounded further below, the foremost output from this chapter is not a specific airworthiness-based design method in itself. Rather, a flexible process for the extraction of design criteria from the regulations and their integration within design methodologies of varying scope has been developed. As brought forward in advance within chapter 3, this is called the DDesign Criteria EXtraction (DECEX) procedure, and its main purpose is to populate design methodologies with airworthiness requirements attending to its scope. Thereby, in essence, it is a process for the development of airworthiness-based design methods. This is demonstrated in this chapter through the application of DECEX for the creation of a particular airworthiness-based design approach itself, which is based on the matching diagram method, and has been adapted attending to the regulatory requirements of RPA.

8.1. Chapter introduction, overview and structure

As commented earlier along the thesis, airworthiness regulations constitute one of the foremost pillars which sustain the high safety levels currently exhibited by the aviation domain (9; 159). Their application ensures that the diverse personnel, organisations, and

technical elements of the aviation system all adhere to rigorous standards in a uniform manner, thus contributing to the safety of the overall aviation system.

The area of aircraft design and manufacturing is governed by a set of standards which cover from the organisational requirements of design and production organisations, up to the specifications with which each product and appliance must comply. This includes the type design of the aircraft, which must adhere to particular certification requirements so that it can be granted a Type Certificate, which constitutes a fundamental step towards ensuring its legal operation within the aviation system. The requirements with which the type design must comply to achieve a Type Certificate are laid out in the certification basis according to negotiations between the applicant and the Authority (159). The bulk of these specifications usually come from detailed airworthiness codes, such as the well-known Part/CS-25 for transport category aeroplanes, or the Part/CS-23 for normal category ones. Certain jurisdictions and aircraft types present significant differences when compared to the above-mentioned classical way of airworthiness type certification, such as ultralights in the USA, which are instead operate on compliance with consensus standards (9). Further details regarding these matters can be found in (9; 48; 159; 184).

Due to the criticality of the design achieving the required certification so that its production units can be legally flown, airworthiness aspects are among those which are most fundamental to be considered along the design process. The purpose of taking into account airworthiness aspects in design is to ensure that the resulting aircraft concept complies with the applicable requirements and is thus certifiable. As seen in subsection 2.1.2, the design process is a gradual endeavour where the aircraft concept is successively refined along several stages. Thereby, and so as to avoid costly redesigns at later design stages, it is essential that these airworthiness requirements are accounted for since the early phases of the design process, as supported by previous authors within the field (7; 8; 9; 15). This is the reason for many classic aircraft design methodologies including within their approaches airworthiness and certification considerations from the early conceptual design phase. Even if the aircraft type does not require to adhere to detailed airworthiness codes, it has been highlighted that the designer should still strive to ensure the safety of the aircraft concept, so in these cases adherence to standards and recommended practices is also recommended (9). Thus, it can be seen that there is a remarkably tight relationship between design methodologies and airworthiness requirements.

As it was already commented within chapter 3, the domain of RPAS regulations is currently a very dynamic area which is still under development. In section 3.2, it was seen that the guiding philosophies and high-level rulemaking criteria of this field present several distinctions when compared to those of the traditional aviation landscape. These aspects have resulted in a significantly different regulatory paradigm than the usual one. In spite of this, the overall principle of considering airworthiness requirements at the design stage to ensure the safety of the aircraft concept would still be applicable, and

various previous works in the field of RPA design have emphasised the integration of regulatory considerations within design methodologies for these aircraft (10; 131; 132).

However, as seen in the results of the regulatory survey conducted in chapter 3, some of the characteristics shown by current standards in the domain of RPAS, as well as aspects pertaining to the regulatory framework as a whole, present significant hurdles towards their integration in design methodologies. A summary of some of the main points raised in the discussion and conclusions expounded in the previously mentioned chapter is provided in Table 8-1. The detailed motives on why these aspects constitute challenges for regulatory integration in design methodologies can be found in the aforementioned chapter.

Table 8-1. Summary of obstacles towards airworthiness-design integration in the field of RPA methodologies, as extracted from the findings, discussions, and conclusions within chapter 3.

RPAS regulatory paradigm characteristic	Challenge in the field of airworthiness-based methodologies
Low current level of harmonisation among international frameworks and specific regulations	Difficulty in developing design methods which can ensure simultaneous airworthiness compliance with diverse paradigms and regulations
Ad-hoc approaches towards the establishment of requirements in certain regulatory areas	As requirements are not laid out in advance, and the level of knowledge of the design usually required to develop the needed safety assessment approaches is high, the possibility of anticipating the applicable specifications at the initial design stages is low
Low level of specificity of many currently available standards	Challenges towards translating the requirements in design specifications with high certificability assurance*
Certain regulatory areas are still under construction	For aircraft which fall within these areas, airworthiness requirements cannot be integrated in the design process, as the specifications themselves are not yet laid out
Ongoing dynamism and changes of the overall RPAS regulatory landscape	This constitutes a challenge not necessarily towards the development of airworthiness-based design methods, but rather to their continued applicability. Regulations themselves and even their overall guiding philosophy have changed significantly along last years, and as mentioned in the previous point, the paradigm is still in construction. Therefore, a design method which has been populated with current RPAS airworthiness requirements might not be applicable in a few years time if the regulations change again

*: the ways in which different specificity level requirements can be integrated within design methods shall be discussed in more detail further along the chapter.

Albeit the works in the field of RPA design of (10; 131; 132) have supported the relevance of integrating airworthiness considerations in the design of these aircraft, and also in spite of the much more widespread incorporation of regulatory aspects in the domain of manned aircraft design (7; 8; 9; 48), up until now, there have been few attempts to consider initial airworthiness requirements in design methodologies for RPA. This was already seen in the overall literature review conducted in section 2.2 as provided within Table 2-2, where it was detected that the topical area of airworthiness-based design is

among the ones with a least amount of references. This situation could be owed to the aforementioned challenges emanating from the novel regulatory paradigm of RPAS, as well as to the comparatively nascent stages of this framework, particularly in the preceding years. Furthermore, the few works that have been found which considered certification aspects in RPA design have either (a) employed regulations of manned aircraft such as Part/CS-25 (133), therefore not accounting for particular rules of RPAS, or (b) employed RPAS regulations that—considering the rapid evolution of the legal field of RPAS—are now obsolete and would not be applicable to develop an aircraft that can be certified or approved for operation in the new paradigm (131; 132). In view of this, both an update to previous design methodologies attending to the new regulations, and also the development of novel design approaches considering RPA certification aspects, would constitute outstanding advancements towards the design of safe and certifiable RPAS.

In view of the above, the purpose of this chapter is to investigate the development of novel airworthiness-based design methods for RPA, particularly within the conceptual design stage, according to the scope of the overall thesis. As seen beforehand, there are significant challenges towards this, including the dynamism of the regulatory paradigm of RPAS, as regulations have experienced notable changes within the last years. Since the paradigm is still not fully established, it can be expected that further variations can occur in the near future. Furthermore, it should also be considered that, when developing a design approach incorporating airworthiness aspects, the specific requirements to be integrated depend on the scope of the design method. For instance, a structural sizing methodology would require to integrate requirements on loads, strength, and deformation, in order to design the structure so it can bear the certification load cases. However, an approach focused on performance would have to incorporate different regulatory requirements. Thus, it can be seen that the applicability of the airworthiness-based design approach is set by the validity of the regulations and the scope of the design topical area which is being covered. This was already brought forward in advance within section 2.2 as illustrated within Figure 2-4, which showed that airworthiness aspects could be integrated in a variety of design approaches.

Thereby, instead of focusing on the development of a particular airworthiness-based design methodology, a different approach is undertaken. The emphasis shall be on the development of a flexible procedure for the extraction of RPAS airworthiness criteria to populate RPAS design methods of generic scope, which is named the D_Esign C_Riteria EX_Traction (DEC_EX) procedure. The purpose of this process is to guide the designer in navigating the complex and challenging characteristics of the regulatory environment so as to choose the airworthiness specifications which can be incorporated (with varying specificity levels) within the design methodology of consideration. This procedure would still be applicable even if the regulations change, since the design approach can be populated with a new set of requirements by changing the corpus of standards that are being considered. Thus, it constitutes a process towards developing airworthiness-based

design methods, rather than a design methodology in itself. The DECEX procedure would represent the foremost novel contribution of the research expounded in this chapter.

Upon having commented the workflow behind the DECEX process, it shall then be employed to generate two design approaches for RPA based on the matching diagram technique, which is a classical conceptual design method proposed in many manned aircraft design manuals (8; 9; 16) and also used in recent research work for this kind of aeroplanes (361; 362). This approach has also been employed in previous RPA design works, such as in (10; 124; 129). However, up until now, and albeit the classic uses of this design approach within the realm of manned aircraft do integrate applicable airworthiness requirements in its process, the previous uses of this approach in the domain of RPA have not included such considerations. Thereby, populating of a matching diagram method with current airworthiness requirements of RPA constitutes an additional novel contribution with respect to previous works that covers a gap related to airworthiness aspects in design, thus aiding to expand the area of airworthiness-based design methods for these aircraft through a particular application of the DECEX process.

The remainder of the structure of this chapter follows the steps outlined here. Firstly, some additional background on the integration of airworthiness aspects within design methodologies shall be developed more in depth in section 8.2, as a theoretical background to the rest of this chapter. Then, in section 8.3, a more detailed literature review on previous works dealing with airworthiness and design integration is conducted. In view of the challenges observed within the state-of-the-art, section 8.4 develops the DECEX procedure, so as to then apply it in section 8.5 to the creation of a design methodology including based on the matching diagram approach where certification constraints have been implemented, following two distinct application cases where the applicable regulations change. Finally, section 8.6 provides the final summary and conclusions related to the airworthiness-based design research of the thesis.

8.2. Integration of airworthiness requirements in design approaches

As detailed in the theoretical background of chapter 2, the aircraft design process encompasses from the initial definition of requirements with which the final design must comply, up to reaching the final definition of the manufacturing blueprints of the aeroplane. As this process of aircraft design is very expansive, it is usually tackled in an incremental approach following a series of stages, which were outlined in subsection 2.1.2. This allows a progressive refinement of the aircraft in such a way that at the first stages, a large design space is explored, and the most promising candidate configurations are evaluated to select those that advance to the next stage (51); whereas, in the final stages, fewer variations are evaluated, albeit these are studied with increased effort and fidelity. This gradual process of exploring and narrowing down the design space in the different design phases is central to the topic of this chapter, as it will be developed below.

A common consensus that can be found within the aircraft design literature is that safety and certifiability of an aircraft are two paramount aspects that the aircraft designer should consider early on in order to ensure reaching a product that satisfies those characteristics (7; 9; 48), and these ideas can also be found in the field of RPAS design (2; 10; 133); albeit, in this latter case, as it will be seen in section 8.3, they have seldom been put into practice through integration of airworthiness aspects within RPA sizing approaches. In any case, the process of considering airworthiness requirements within design methodologies is not straightforward, as it will be seen through this section. Even in the more harmonised and mature area of manned aircraft airworthiness and design, this process presents several hurdles that the designer must surmount, to which the additional obstacles resulting from the particularities of RPA should be added when considering the objective of developing airworthiness-based design methodologies in this thesis.

Firstly, it should be noted that a series of characteristics of the design methodology which is sought to be populated with airworthiness requirements can have a remarkable influence in the process airworthiness-design integration. These shall be expounded in detail along this section. However, a brief outline is provided below:

- **GDM and AADM:** the concepts of these two types of design approaches were introduced in subsection 2.1.3. Albeit airworthiness requirements can be integrated in both cases, the approaches are slightly different, since GDM place emphasis on broad applicability, whereas AADM are focused on a particular design case.
- **Aircraft regulatory category:** airworthiness regulations have different applicability scopes, being valid only for aircraft falling within certain categories. For instance, the requirements contained within Part/CS-23 and Part/CS-25 regulations are starkly different, and each of them applies to a certain aircraft type, with these being normal-category aeroplanes and transport-category aeroplanes, respectively. Thereby, depending on the characteristics of the aircraft to be designed, the applicable airworthiness codes vary, and thus the requirements to be integrated.
- **Design methodology scope:** this is related to the topical area covered by the design approach, which is not only related to the aircraft type (for instance, a design method for transport-category aeroplanes), thus being connected with the point above, but it is also tightly linked with the disciplines that are being accounted for.
- **Phase of the design process:** the kinds of airworthiness requirements that can be considered also depend on the stage of the design continuum in which they are sought to be integrated. This is due to the level of definition of the aircraft being starkly different in distinct phases. Furthermore, this area is also linked with that

of the design methodology scope. This relationship was discussed in sections 2.1 and 2.2, and it was also illustrated in Figure 2-4, where it was seen that there is a relationship between the design phase and the typical disciplines that are studied within it.

With respect to the resulting considerations related to airworthiness-design integration depending on whether the design approach is of the GDM or AADM type, the nature of the process presents certain differences for each case. Within GDM, the emphasis is on wide applicability of the systematic design methodology. Thereby, a more ample array of airworthiness requirements, typically pertaining to different regulations, usually have to be considered, so as to ensure that the range of validity of the method covers sufficient ground. This is, for instance, the case of Roskam's matching diagram approach, which considers both Part-23 and Part-25 requirements, so the corresponding set of constraints can be applied to aircraft from both certification categories (8). On the other hand, in the case of AADM, the airworthiness integration process is usually more straightforward, as these kind of design approaches are already focused on a particular design case, so they only need to study and integrate the applicable regulations for the specific aircraft that is being designed.

As seen above, in the case of GDM, considering different aircraft types within the applicability range of the design method can lead to the necessity of integrating diverse sets of airworthiness constraints. This is linked with the second point as seen above, which is that of aircraft type. Usually, design methodologies, particularly those of the GDM kind, are focused on a specific type of aircraft, such as transport-category aeroplanes (7; 51), or general aviation aircraft (9). The differences of airworthiness requirements for diverse aircraft types are often so remarkable that distinct approaches have to be considered altogether, as seen in the previous references.

The scope of the design methodology includes the above-mentioned aircraft type distinction, but it also covers aspects such as the disciplines considered within the design approach and also the design phase for which it is developed. For instance, classic design manual approaches are usually mainly focused on the conceptual design stage (7; 8; 51). As expounded in subsection 2.1.2, the design phase is also tightly linked to the disciplines which are being considered, which is also a fundamental point influencing the integration of airworthiness constraints. For instance, a design approach focused on initial sizing based on performances would typically extract certification requirements from the Subpart B – Flight, of typical Part/CS codes, since it covers performance considerations. This type of design approach would be typical of early conceptual stages. On the other hand, a design method focused on structural sizing would obtain the applicable airworthiness considerations from Subpart C – Structure, and this kind of approach would be more usual of late conceptual or early preliminary stages. Thereby, the requirements to be integrated from the regulations are also largely dependent on the scope of the design methodology to be populated with them, as the certification constraints or aspects that

are considered should be those that affect the main design variables of interest within the limits of the design method.

As brought forward in advance before, the process of extracting applicable certification requirements and integrating them within design methodologies is a complex task. Previous works such as the one of (49) in the manned aviation domain have commented the challenges that arise, with some of the most noteworthy being:

- 1) The difficulties resulting from having to consider several documents at the same time and finding the relevant requirement within each of them.
- 2) Several regulatory documents giving at times different requirements for the same design variable.
- 3) The regulations often not specifying quantitative criteria, being more qualitative in nature and thereby not establishing specific numerical constraints. It is noted that this is tightly linked with the characteristic of “level of specificity” which was among the dimensions proposed for the regulatory evaluation within chapter 3. In fact, as mentioned there, one of the main reasons for including this feature was the fact that this aspect has been considered within previous works as one of the main hurdles towards airworthiness-design integration.

The issue of having distinct requirements in different regulatory documents has also been remarked, albeit outside design processes, in the work of (396), which commented on the issues of verifying the criteria of all documents simultaneously. This serves to highlight the relevance of the regulatory paradigm being homogeneous and harmonised, connecting with some aspects with respect to the recent harmonisation efforts within the regulatory field of RPAS, as commented in section 3.2. As it will be seen through this chapter, the second and third points listed above constitute some of the paramount hurdles towards design-airworthiness integration in the field of RPA. In particular, it was already seen in chapter 3 that most current regulations showcase a low specificity level, thus underscoring the expected impact that the aforementioned third consideration shall have in the efforts developed within this chapter.

With respect to this challenge of certain certification requirement being more qualitative in nature and not establishing specific compliance criteria, some possibilities of tackling this issue are outlined here. In the same way that airworthiness requirements can be qualitative or quantitative, as mentioned beforehand, aircraft design methods employ both quantitative and qualitative tools. An example of the former are the second segment climb flight mechanics equations, which can serve to select the take-off thrust/weight ratio in a matching diagram (8). In contrast, a case of the latter could be the general arrangement selection criteria for choosing the most appropriate combination of tail layout, engine position, etc. Thereby, different possible ways of integrating the lower specificity requirements in aircraft design methods can be outlined:

- One way to would be to include them as considerations that the designer must take into account so as to make high-level decisions with respect to the design, such as the selection of a certain layout, in such a way so as to aid in complying with these qualitative requirements. Thereby, qualitative design criteria could be enhanced by including these type of certification requirements.
- Another alternative could be to use these qualitative requirements to aid in identifying variables of interest which can affect the compliance with the requirement. For instance, a low specificity requirement stating that the aircraft should have adequate stability and control characteristics could point towards variables such as the tail surfaces or tail moment arm, as they influence the aspects being stated within the requirement.
- Another option, which links with the previous point, could be to generate numerical constraints from the low specificity requirements, in order to aid in substantiating the compliance in a more precise manner. Having identified the key variables through the previous alternative, different sources or established design methods could be employed to establish quantitative restrictions.

Previous works have sought to tackle the aforementioned low level of specificity challenge. In the research of (397), qualitative stability and control requirements in the Part/CS-23 were integrated into the flight test phase to evaluate whether the dynamic response of the aeroplane was adequate. On another but related subject, the work of (80) for manned aircraft disruptive technologies proposed a process of seeking additional documents and standards to fill the gaps in a manner that could be expected to yield positive results when negotiating the certification basis with the Authority. Overall, it is clear that the process of integrating certification requirements in design methods requires specific procedures and strategies to tackle its main challenges.

There is an additional design-airworthiness integration aspect related to the aforementioned level of specificity considerations, which is their effect on the boundaries and evolution of the design space. As mentioned beforehand, aircraft design follows an incremental approach, where the design space is explored more broadly in the first stages but more in depth in later ones. Therefore, it is expected that, before the onset of further stages, the design space is narrowed down to the most promising configurations in order to avoid employing excessive time and resources in the later phases. During this process, it is relevant to avoid the aircraft from converging to undesired alternatives when narrowing down the design space. Related to this, it is also critical that the design convergence ensures that the remaining aircraft concepts are certifiable, at least within the scope of certification that is being studied at the design stage being considered. Although the restrictions that may result from airworthiness regulations could reduce the design space, thus eliminating potential candidates, they do so while providing in compensation an increase in confidence of the certifiability of the remaining designs,

which is crucial for the designer and facilitates that the process converges in designs which are airworthy and safe.

When requirements have a high level of specificity, they establish “hard restrictions” in the design space that limit its boundaries, but in compensation, the confidence in the certifiability of the remaining design space is high. When dealing with low specificity requirements, the designer might have to derive design restrictions based on qualitative guidelines, so the constraints are not “clear-cut” and may thus provide certain flexibility to the design; on the other hand, the level of confidence in the certifiability of the designs is lower, as a clear and detailed criterion was not given by the Authority. Therefore, it can be seen that the level of specificity of regulatory requirements can have not only a significant effect on how they are integrated in an aircraft design methodology, but also on their potential effect in the design space. The above concepts regarding the differences that can result in a constrained design space when considering requirements with differing levels of specificity are illustrated in Figure 8-1.

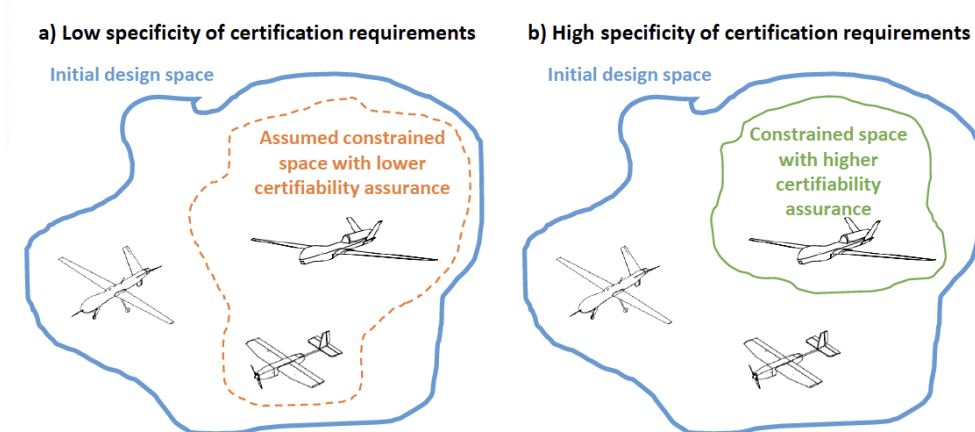


Figure 8-1: Conceptual representation of difference in breadth and certification assurance of constrained design spaces according to requirements of differing levels of specificity. Some candidate designs may be left out in the case of a higher specificity level but, as a trade-off, the assurance in certifiability can be expected to be higher.

The concepts developed through this section have a key impact on the research to be conducted in this section, particularly since the regulatory field of RPAS presents heightened challenges in relation to the three main hurdles as specified by (49). Firstly, the regulatory framework is still in its development process, and there are also many aspects to address regarding harmonisation, as discussed in section 3.2 and evidenced through the findings of the survey developed within section 3.5. This magnifies the first two challenges related to the variety of documents and the disparity of requirements among distinct regulations. Furthermore, in relation to the third point, as it was seen in the survey conducted within section 3.5, RPAS regulations present varying levels of specificity not only amongst outstanding documents but even between different requirements given within the same regulation. This highlights the need to develop

procedures that aid the designer in navigating regulatory requirements with different characteristics so as to aid their effective integration within RPA design, which is the main topic of the investigation presented in this chapter.

8.3. Previous works in design and airworthiness integration

Having seen the main particularities and challenges pertaining to the field of airworthiness-based design, this section contains an overview of previous works dealing with aspects related to both the fields of design and airworthiness.

As it was already seen in section 2.2, there is currently only a small number of works within the field of RPAS that have taken into account airworthiness aspects in design. Therefore, this section also includes several works from the manned aviation domain, ranging from classic design manual approaches, to recent research works. In spite of the field of RPAS design-airworthiness integration presenting heightened challenges in this regard, the ways in which manned aviation research has tackled the main issues of this domain shall also serve to guide the decisions made when conducting the research of this chapter. It should be noted that this state-of-the-art overview is distinct, but complementary, to that which was conducted in section 3.3, with it being instead focused on works that had conducted reviews on the regulatory paradigm of RPAS. Here, in contrast, several works are analysed from the fields of manned aviation and RPAS design, some of which have integrated airworthiness aspects within the design continuum. The main text contains an overview of these works and the main trends of this domain within the state-of-the-art, whereas Table 8-2 contains a more detailed overview of each of the cited investigations.

Within the field of traditional manned aviation aircraft design, many works have considered the requirements of certification regulations in the design process, starting from well-established textbook methodologies such as the ones in (7; 8; 48), which integrate FAR and CS requirements in aircraft conceptual and preliminary design procedures; moving on to recent works that have developed certification-driven analytical and optimisation methodologies considering various certification paradigms and requirements, such as certification analysis of general aviation aircraft (49), noise regulations (398) and even hydrogen-fuelled aeroplanes (399); to research seeking to include certification considerations within MDO frameworks including computerised design environments (90; 248). It should be noted that the systematic process of extracting design requirements for their integration in design methodologies has been given significant attention in these previous works (49; 90; 248), as it was mentioned in section 8.2. that this is one of the main ways to include airworthiness aspects during the first stages of design. This approach is also employed in works where the main aircraft architecture has already been decided, along with the use of safety assessment methodologies, in the context of certification of disruptive technologies, such as in the work of (24), or in the development of aircraft systems with a safety perspective such as

in (174). Aside from the applications in aircraft design, it is also clear that the broader area of airworthiness of manned aviation is notably dynamic, with recent works such as those of (400; 401; 402; 403) covering different dimensions of this field, discussing some challenges in airworthiness and certification considering the evolution of the aviation paradigm, and showing a continuous interest in it.

Moving on to design methodologies for RPA, as already mentioned beforehand, their design presents several challenges that are different to that of manned aircraft, requiring specifically tailored design approaches to account for their particularities (15). The field of research of design methodologies for RPA is considerably prolific: from textbook-based approaches such as those of (6; 10); moving on to statistical results to employ in initial estimation tasks (46); design approaches based on design restrictions and optimisation, such as in (62; 128); and even computerised design environments (115). These distinct topical areas and perspectives were analysed in detail within the review of chapter 2. In contrast, and in spite of the recognised relevance of considering certification aspects in the design process, there are currently very few works within the field of RPAS that have dealt with the combination of the disciplines of airworthiness and aircraft design simultaneously, and on how airworthiness requirements might impact the design of the RPA. For instance, the work of (10) supports the relevance of integrating airworthiness aspects in RPA design and explains the main structure and contents of NATO Standard AEP-83, recommending the designer to check various typical design constraints related to certification. However, these are not integrated in a design workflow per se, and their effect on key design parameters is not demonstrated. On the other hand, the work of (133) is remarkable in that there is an extraction of regulatory requirements, demonstrated through a particular case of considering lightning protection aspects, to integrate them at an optimisation stage of the RPA design; however, in this case, the requirements were obtained from Part/CS-25 regulations, thereby not employing RPAS-specific rules. Moving on to the works of (131; 132), they developed design approaches using RPA regulations in their specific areas (systems weight estimation, and structural weight estimation, respectively) upon extracting specific requirements within their scope. However, many years have passed since these works were conducted; thus, the regulations employed therein have since been repealed.

Table 8-2. Overview of main characteristics of selected works within the state-of-the-art pertaining to airworthiness and design aspects, with a main focus on the integration of airworthiness aspects within aircraft design activities. The column “Design Stage Focus” evaluates references attending to the aircraft design stage taxonomy used through this thesis. References are organised attending to citation order within the main text.

Reference	Aircraft Type	Design State Focus	Research Scope	Airworthiness Regulations and Integration in Design Activities
Torenbeek (7)	Manned	Conceptual and preliminary: rapid, low-fidelity methods	Full concept synthesis and initial sizing of subsonic aircraft. Encompassing design approach covering performance, aerodynamics, structures, stability and control, powerplant aspects, etc.	Integration of FAA and CAA regulations in many aspects and sizing procedures. For instance, requirements for performance in matching diagram, structural requirements in manoeuvring envelope, stability and control requirements for tail sizing, etc.
Roskam (8)	Manned	Conceptual and preliminary: rapid, low-fidelity methods	Full concept synthesis and initial sizing of civil and military aircraft. Encompassing design approach covering performance, aerodynamics, structures, stability and control, powerplant aspects, etc.	Integration of FAA regulations and certain military standards in many aspects and sizing procedures. For instance, requirements for performance in marching diagram, cabin layout, stability and control requirements for tail sizing, etc.
Stinton (48)	Manned	Conceptual and preliminary: rapid, low-fidelity methods	Full concept synthesis and initial sizing of aircraft, with a focus on light aircraft. Encompassing design approach covering performance, aerodynamics, structures, stability and control, powerplant aspects, etc.	Various considerations: FAA, JAA and CAA certification categories and applicability ranges; analysis of main paragraphs regarding flying qualities and performance; evaluation of impact in design areas and relation with relevant variables; limits for pilot effort when sizing control surfaces, etc.
Tyan et al. (49)	Manned	Conceptual and preliminary: rapid methods and optimisation	Initial OML layout sizing and optimisation of general aviation aircraft attending to regulatory requirements	FAR 23 and Korean Airworthiness Standard (KAS) KAS 23 regulations. Dedicated procedure for elaboration of certification database and requirement extraction. Consideration of variable constraints attending to regulatory restrictions within optimisation procedure and final compliance check
Nöding and Bertsch (398)	Manned	Preliminary: simulation framework with multiple disciplinary modules	Evaluation of transport aircraft noise in relation to take-off and approach trajectories and design parameters, such as fuselage geometry and MTOM. Sensitivity studies evaluating contributions of engines and airframe	Aircraft noise metrics as well as take-off and approach trajectories according to ICAO Annex 16 regulations are evaluated for the design concepts analysed with the simulation framework
Spencer (399)	Manned	Preliminary: systems architecture, engineering and safety	Evaluation of current airworthiness codes limitations towards certifying hydrogen-fuelled aeroplanes, considering the main aspects of hydrogen power systems	Analysis of current CS-25 certification requirements affecting the propulsion system (crashworthiness, explosion prevention, etc.) and discussion on gaps in their application to the certification basis and design of hydrogen aeroplanes

Reference	Aircraft Type	Design State Focus	Research Scope	Airworthiness Regulations and Integration in Design Activities
Schmollgruber et al. (90)	Manned	Conceptual and Preliminary: MDO framework	Development of a dedicated certification module within the design package FAST. The module allows to manage the certification constraints established by the regulations and their integration in an MDO process	The certification module allows a formal representation of the relationships between CS-25 regulatory requirements and key design variables in UML format, standardising their representation and integration into design MDO workflows as optimisation constraints
Xie et al. (248)	Manned	Preliminary: MDO framework	Proposal of a certification-driven environment for the integration of certification constraints in multi-objective airframe optimisations. Case study of horizontal tail refinement attending to flight mechanics requirements	The flight characteristics module checks, for the input aircraft geometry, a series of characteristics extracted from the regulations, mainly requirements from CS 25 Subpart B and Subpart C to check both flight mechanics and structural compliance
Travascio et al. (80)	Manned	Preliminary: systems engineering	Once a system architecture for a disruptive concept such as a hybrid propulsion system) has been defined, a procedure is proposed to identify certification basis gaps from existing regulations in order to propose modifications or introduction of new requirements through a safety assessment process	Regulations such as CS-25, CS-E and CS-P are analysed for potential requirements considering the system architecture of study. The gaps in the requirements are covered by generating a proposal of means of compliance that are obtained through a safety assessment of the system design
Jeyaraj et al. (174)	Manned	Preliminary: systems engineering and MDO	Development of a methodology to introduce safety assessment earlier in the design continuum, focusing on system architecture and safety analysis, towards seamless integration in MDO approaches	Regulatory requirements for systems, such as those of Part 23 or Part 25 (as stated in an application example), are included through a safety filtering method that analyses proposed architectures and keeps those that comply with the requirements
Insley and Turkoglu (400)	Manned	Not applicable	Analysis of commercial air transport accidents and serious incidents related to maintenance, supplemented with opinions gathered from experts, in order to identify main factors and high-risk areas	No regulatory requirement integration in design methodologies
Habib and Turkoglu (401)	Manned	Not applicable	Study of general and commercial aviation accidents and serious incidents in the context of Nigeria, complemented with a survey from subject matter experts, to identify root causes and main areas of concern	No regulatory requirement integration in design methodologies
Rötger et al. (402)	Manned	Not applicable	Review of current regulations applicable to supersonic transport aircraft and current rulemaking activities. Discussion on prospective regulatory aspects to be covered in future rules	No regulatory requirement integration in design methodologies

Reference	Aircraft Type	Design State Focus	Research Scope	Airworthiness Regulations and Integration in Design Activities
Kusmierek et al. (403)	Manned	Not applicable	Survey of opportunities and challenges of hybrid propulsion systems considering the demands of emission regulations and objectives. Evaluation of different system architectures and trends of aircraft equipped with these powertrains	No regulatory requirement integration in design methodologies
Sóbestor et al. (15)	RPAS	Conceptual and preliminary	Development of a geometry service to produce and modify both the OML and the structural layout of RPA. Evaluation of weight, wing loading and power loading trends for RPA	No regulatory requirement integration in design methodologies
Gundlach (6)	RPAS	Conceptual and preliminary: rapid, low-fidelity methods	Full concept synthesis and initial sizing of RPAS. Covers many aspects of RPAS design, not only including those of the air vehicle: aerodynamics, performance, structures, powerplant aspects, payload and communications, command and control, etc.	As the regulatory framework of RPAS was still incipient, the regulatory considerations considered in the method have mainly been adapted from manned aircraft regulations
Keane et al. (10)	RPAS	Conceptual, preliminary and detailed design	Full coverage of the different stages of RPAS design, mainly focused on small RPA. Conceptual design methods are mainly focused on rapid approaches such as the matching diagram, preliminary methods usually employ optimisation, and detailed design aspects are mainly focused on final geometry definition for manufacturing	The relevance of integrating airworthiness aspects in RPA design is supported, and the main structure and contents of NATO Standard AEP-83 are explained, recommending checking various typical design constraints towards certification
Gómez-Rodríguez et al. (38)	RPAS	Conceptual: statistical approach	Analysis of a database of RPAS, evaluating general design trends with respect to layout and powerplant, and development of a rapid sizing method for H-tail RPA based on correlations obtained from the database	Thresholds for MTOM towards design trend analysis established in part attending to regulations at the time of research; however, some of these are no longer applicable
Mitridis et al. (40)	RPAS	Conceptual: statistical approach	Analysis of a database of RPAS attending to the NATO classification, analysing key categorisation aspects and design parameters through correlations, dot plots and box plots	No regulatory requirement integration in design methodologies
Champasak et al. (62)	RPAS	Preliminary: multiobjective optimisation	Development of a metaheuristic-based optimisation framework for RPA design incorporating reliability aspects. Four case applications are conducted based on pre-defined value ranges for optimisation variables	No regulatory requirement for integration in design methodologies

Reference	Aircraft Type	Design State Focus	Research Scope	Airworthiness Regulations and Integration in Design Activities
Tyan et al. (128)	RPAS	Conceptual and preliminary: rapid, low-fidelity methods and optimisation	Initial sizing of a hybrid fixed-wing VTOL small RPA using rapid sizing procedures and a matching diagram constraint approach. Further optimisation and resizing of the vehicle starting from the initial concept	Maximum flight height of Part 107 regulations is considered as the cruising altitude of the RPA
Aliaga-Aguilar and Cuerno-Rejado (115)	RPAS	Conceptual and preliminary: rapid methods towards integration in MDO	Development of aerodynamic and performance modules towards their integration within an MDO-driven computerised design environment for small RPA	No regulatory requirement integration in design methodologies
Torrigiani et al. (133)	RPAS	Preliminary: MDO framework with multiple disciplinary modules	Starting from an initial MALE RPA concept, it is optimised through the use of the AGILE framework comprising multiple modules, from geometry definition to aerodynamic calculations including systems engineering	Consideration of CS-25 regulatory requirements, particularly particular lightning protection, with respect to systems engineering in the requirements definition and optimisation process, accounting for systems interaction
Casarosa et al. (131)	RPAS	Conceptual: rapid weight estimation method	Analysis of RPAS onboard system requirements and trends towards developing a rapid weight estimation method for the take-off weight of a certifiable RPA. Use of statistical data of onboard equipment to develop the estimation approach	Definition of the minimum equipment required and redundancies attending to airworthiness design requirements available for civil RPAS at the time of publication, particularly safety targets. This information is employed to estimate the required equipment and, from the statistical data, the weight
Cuerno-Rejado and Martínez- Val (132)	RPAS	Conceptual: rapid, low-fidelity methods	Development of a rapid approach towards estimating RPA required structural weight to withstand gust and manoeuvre loads prescribed by applicable regulations. Evaluation in a case study of various existing RPA to compare the structural weight required to comply with the regulations with the actual one	Considering the EASA Policy E.Y013-01, which allows to derive requirements for RPA through the tailoring of manned aviation certification codes, the corresponding applicable codes are obtained for various existing RPA, and from the requirements, for each of them, the gust and manoeuvring requirements are derived

The main conclusion which can be extracted from this analysis is that there is still room for improvement in the field of design-airworthiness integration within the domain of RPAS. This is consistent with the previous outline of this area which as seen in section 2.2, which is now backed up by the more in-depth review conducted in this section. The low development of this field of RPAS design can be understood when considering both the fact that the RPAS regulatory framework has only just recently experienced a noteworthy development, as well as the heightened issues associated with the integration of airworthiness requirements in RPAS design methods as discussed in the previous section.

Thereby, the findings from this state-of-the-art analysis consolidate the decision on the focus on airworthiness-based design methods as one of the main three branches of the work developed in part III of this thesis. As outlined in the introduction of the chapter, instead of focusing on the development of a specific airworthiness-based design approach, and in view of the main challenges of the field of RPAS, the emphasis has been on devising a flexible procedure for design criteria extraction from airworthiness regulations, named DECEX. This can then be applied to populate design approaches with certification requirements. Both the development of DECEX, as well as its use towards creating design methods based on the matching diagram process, shall be covered in the following section.

8.4. Flexible procedure for Design Criteria Extraction (DECEX)

This section shall tackle the investigation of new procedures that can aid the designer in navigating the complex regulatory landscape of RPAS and integrating airworthiness considerations in the design continuum, particularly within its first stages. As mentioned beforehand in the introduction, the emphasis is on the development of a flexible procedure for design criteria extraction, which has been named DECEX, which will then be applied to two cases in the following section in order to showcase its capabilities in populating design methodologies with airworthiness requirements.

The connection of the present section with the survey conducted in section 3.5 should be highlighted, as not only does it constitute the main body of documents that can be used with the procedure but it has also revealed key challenges that the designer must face when navigating the regulatory paradigm and integrating airworthiness aspects in design. Precisely, the DECEX approach has been developed taking those findings into account, as it will be developed in detail along the current section. Furthermore, the characteristics that were defined in subsection 3.4.1 and used in the review of regulations within chapter 3 shall also be employed here.

8.4.1. Rationale for the Development of the DECEX Procedure

The review conducted in section 3.5 did not only focus on airworthiness aspects but also on how the characteristics and content of the different regulations, and the paradigm as a

whole, might impact the RPA designer and the integration of certification aspects in RPA design methodologies. As mentioned in the introduction and in the literature review, there is still work to be conducted in the general area of RPA design, and more particularly, in certification-driven RPA design. Considering the current regulatory paradigm, which is more developed and harmonised than some years ago, and the relevance of integrating certification aspects in design, as already discussed in section 8.2., there would be remarkable potential in the development of new RPA design methodologies integrating airworthiness considerations that are up-to-date within the current paradigm and even in updating previous methodologies with the new requirements. It should be noted that the focus here is not on developing a specific design methodology or the integration of certification aspects in a particular design process. Rather, it is on the development of the design methodologies themselves, as this can potentially have a farther reach, as multiple possible future airworthiness-driven approaches could benefit from it rather than only one design methodology, which in the end is developed with a particular scope with respect to the design stage and the disciplines considered. This can be considered one of the novel aspects of this work in that the objective is to define a procedure that can be applied to populate different design methodologies with airworthiness aspects, augmenting its applicability and reach.

The main rationale behind the development of DECEX is that, if a designer seeks to develop a new airworthiness-based design methodology for RPA, or when conducting the design of a specific RPA accounting for certification aspects, they face many issues in the process of navigating the regulatory landscape and extracting the desired requirements from the regulations to integrate them in the design continuum. Some of the outstanding challenges, as anticipated in the discussions presented along the survey, are summarised below:

- Firstly, the designer requires a common reference of all the potential applicable regulations, the requirements of which might be extracted. Albeit in the field of manned aviation the potential regulations are clearer and well-established; in this case, as seen in the aforementioned sections, the material is more spread out. It could be said that this point has been tackled, at least within the scope of this work, through the survey conducted beforehand in this thesis.
- There is a notable heterogeneity not only in the main characteristics of the regulations as evaluated with the criteria proposed in subsection 3.4.1. but also in their content related to specific topics (such as the definitions and requirements with respect to airspeeds, as commented in subsection 3.5.2), which is in contrast with the comparatively more homogeneous manned aviation paradigm.
- There is a general lack of publicly available high-specificity regulations and standards for the certified category of RPAS. As commented in section 8.2, detailed provisions are the ones that can be most easily integrated in quantitative procedures, and they also provide larger certifiability confidence.

- Adding to the above issues, even if detailed consensus standards were accessible to complement low-specificity requirements in the main texts, there are no detailed directions for the correspondence of the requirements in the main regulation with the applicable standards to demonstrate compliance with that particular requirement.

Adding to the above issues, even if detailed consensus standards were accessible to complement low-specificity requirements in the main texts, there are no detailed directions for the correspondence of the requirements in the main regulation with the applicable standards to demonstrate compliance with that particular requirement.

It should be noted that some of these challenges are similar to those found in the work of (49) when developing their framework for design-airworthiness integration for manned general aviation design. These challenges were commented in section 8.2. However, in the field of RPAS, these issues (for instance, the differences between the requirements established by differing documents) have been found to be of greater magnitude due to the characteristics of the paradigm. It could be argued that the issue commented in the first point within the list above is in part covered by the survey developed in this work; however, the challenges related to the extraction of the requirements from the regulations and their integration in design methodologies remain. Seeking to mitigate these issues that the RPA designer is expected to find in view of the current regulatory paradigm, a procedure is proposed to aid both in the extraction of design criteria from this complex landscape as well as in their integration to design methodologies. The scope and nature of the DECEX procedure presented here is not that of a design methodology per se, as mentioned beforehand. Rather, it is a procedure that accounts for the previously analysed issues in the RPA regulatory landscape in order to aid the designer to extract the applicable criteria that can be integrated into RPA design methodologies. Therefore, the nature of DECEX is that of a procedure that aids in the comparison and extraction of certification criteria from a set of applicable regulations so as to integrate certification-based aspects into existing or novel design methodologies according to their scope, which can then employ these regulatory criteria to perform the sizing of aircraft, improving their certifiability. The nature of the procedure and its connection with design activities can be more clearly seen in Figure 8-2, which will be commented shortly.

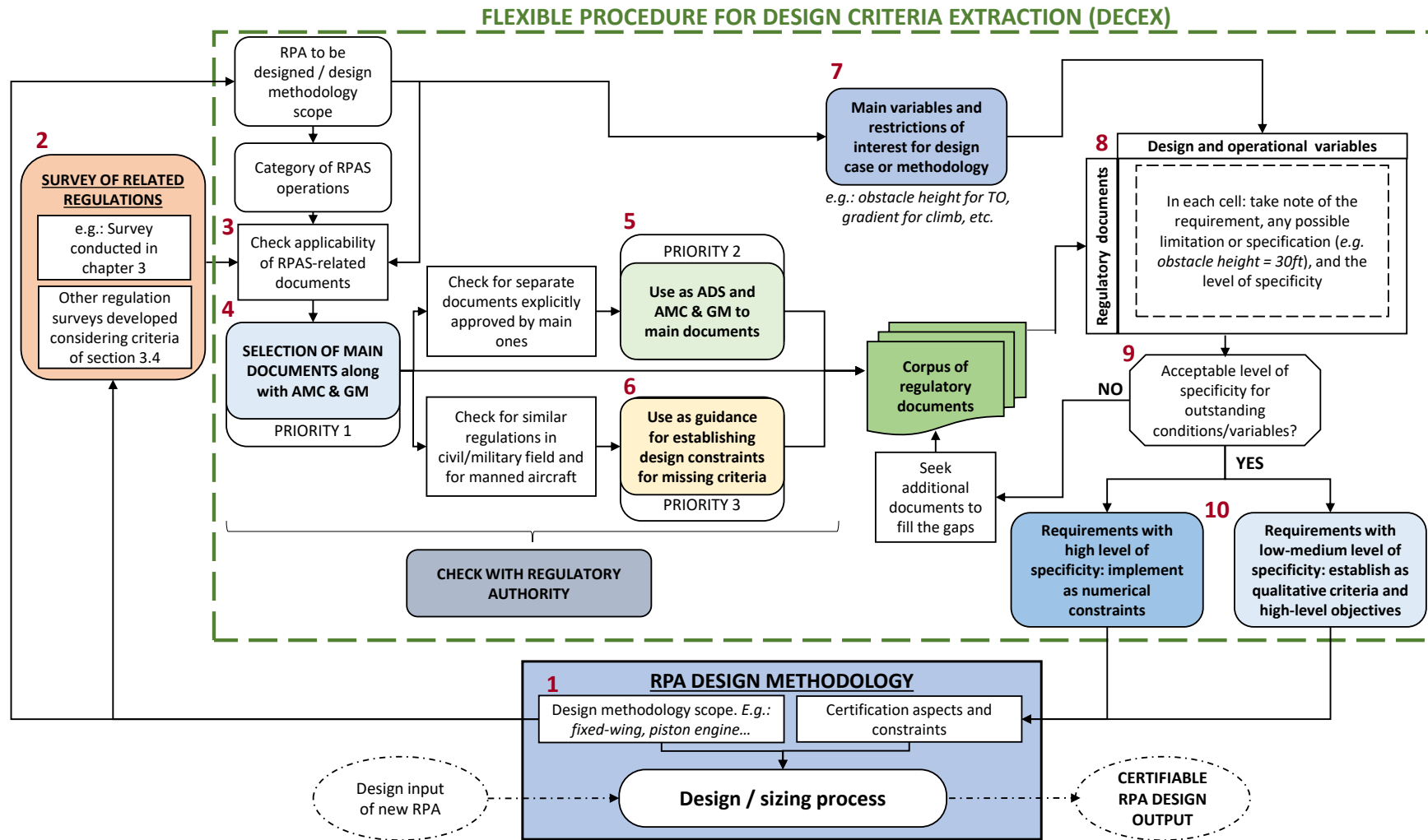


Figure 8-2: DECEX procedure workflow. This schema has assumed that a GDM approach is being populated with airworthiness requirements; however, it can also be applied directly to a design process, accounting for its scope in step 1. The numbers indicate the main workflow highlights and are commented in the main text.

This process of transforming regulatory requirements into design criteria, which is the main focus of DECEX, was already commented in section 8.2 as presenting a series of challenges, has already been tackled by previous works within the manned aviation paradigm (49; 398), and automatic procedures for conducting this process have even been integrated in computational design environments and MDO frameworks (90; 248). However, no such work has been developed for the field of RPAS, accounting for their particularities and considering the current regulatory paradigm; thus, this constitutes one of the novel contributions of this research to the state-of-the-art. It should be highlighted that, in order to prepare for future possible changes in RPAS regulations (which are to be expected, as it was seen for instance in section 5.2. that rulemaking is still ongoing in areas of AI and new materials, amongst others), and also for cases where different regulations than those analysed in this survey are considered, the procedure was developed so as to be flexible and adaptable. These characteristics of flexibility and adaptability are not only considered with respect to the regulations that can be integrated but also from the viewpoint of the design approach to be populated with airworthiness requirements, as different design stages and methodologies may place emphasis on certain disciplines (such as structures, or stability and control) and have different objectives with respect to the level of detail of the requirements to be integrated, as commented in section 8.2. Therefore, DECEX has been conceived to be applicable to a variety of types of design methodologies in order to further improve its usability, which is a desirable characteristic for certification- driven procedures, as highlighted in previous work (49), and can be considered one of the main contributions of the methodology. This flexibility also lends itself to future work in extending the DECEX approach to further design stages, such as preliminary design or systems engineering approaches, which also employ the airworthiness criteria extraction and integration perspective along with other safety modelling approaches, as commented beforehand.

8.4.2. DECEX Application Workflow

The main workflow of the DECEX procedure is illustrated in Figure 8-2 and is explained below, following the main steps highlighted in the schema:

- 1) As the objective is to integrate airworthiness aspects within a design methodology or process, the first stage, in accordance with the theoretical background commented in section 8.2, is to establish the topical scope of the design activity. This mainly includes the design stage of interest and potential disciplines of consideration.
- 2) Then, a search is conducted to find the main applicable regulatory documents, accounting for the aforementioned scope. It should be noted that the survey conducted in section 3.5 can constitute this step for design activities mainly related with the RPA airframe and dealing with early design stages. If the scope is different, other documents can be reviewed here for integration in the procedure.

If the regulations change, this step can be modified to integrate the new applicable documents, in order to update the design approach according to the novel regulations by following the procedure from here.

- 3) At this point, and in view of the documents that have been reviewed, the ones applicable to the design methodology scope are selected for the next stages. This will also be dependent on the category of operations associated to the expected output design and the operational scenario. Table 3-3 and Table 3-4 provided in this work can be consulted for this stage. Only those documents that are applicable continue on the next step.
- 4) In the next steps, the corpus of documents from which regulatory requirements will be extracted shall be selected, with different priority levels depending on the degree of correspondence to the scope of the design activity. The main idea behind this is to have, aside from the main ones, other documents to attend to in case the foremost ones have a low level of specificity such that it is preferred to seek clearer and quantitative requirements in others, and also to compare the restrictions set by the different ones. This process of selecting alternative regulatory documents to use when the main ones do not achieve the desired characteristics, or to complete their gaps with requirements from others, has been used in previous works (49; 80) within the manned aviation paradigm to great effect. Firstly, those documents that are directly aligned in applicability (as in the results of stage 2 of the survey in subsection 3.5.2.) to the scope of the design activity, are labelled as “Main documents” along with their AMC and GM.
- 5) Having selected the main documents, and as the issue of low level of specificity is widespread in the field of RPAS regulations, as it was seen in the review, a second group of documents is selected. These will be those that are explicitly referred to in the main documents, which can serve as ADS or complimentary material to the main ones. For instance, CS-UAS explicitly recommends the use of CS-LUAS as ADS for cases where the latter is applicable within the CS-UAS paradigm. It has been noted in subsection 3.5.1 that the correspondence between main documents and their ADS is seldom stated in a direct way in the field of RPAS, which complicates this step, and this is the reason for considering a third group of documents.
- 6) The third group of documents are potential documents that, even if not directly applicable to the design case, are other reputable references that may aid in filling the gaps from the first and second groups. For instance, if the RPA is being designed within the civil domain, military RPAS regulations can be considered here or even manned aviation documents applicable to a similar MTOM range. Even outside the design process, upon seeking approval by the Authority of the certification basis, these other documents can be useful to seek for alternative and more detailed proof of compliance approaches for those points in which the applicable main documents are not detailed. All of this generates a corpus of

documents where the potential specificity gaps of the primary ones can be covered by the secondary and tertiary references.

- 7) For the next step, it is necessary to define with more detail the relevant variables related to design aspects that are related to the scope of the methodology: geometric, performance, structural, etc. Specific variables should be defined, such as climb gradient, stall speed, obstacle height for take-off, etc. This will serve for the next step, where specific requirements will be sought within the documents in relation to the design aspects of interest.
- 8) Now, having both the corpus of documents and the regulatory documents of the three levels, the next step consists of examining each of those references for the applicable requirements for each design variable of interest. These are compiled in a table, as seen in Figure 8-2, in such a way that for each variable, the applicable aspects from each document are compiled. At this point, the specificity would be evaluated at requirement level, instead of for the whole document, which was anticipated in subsection 3.4.1. when defining the level of specificity criterion. Furthermore, this allows a direct comparison of the similarity and differences in the content of the requirements, allowing to detect, for instance, heterogeneous limit values for certain restrictions.
- 9) Once the table has been crafted, the level of specificity for each variable is evaluated for the group of documents. If any gaps are identified, for instance no high level of specificity requirement having been found for certain variable, more regulatory material can be sought
- 10) Considering the results from the table, these are translated to the design methodology in one of two forms. For those variables for which a high level of specificity has been found, the requirement can enter the design activity as a quantitative constraint in the relevant equations or in the optimisation process. Those variables for which this condition is not achieved are not discarded; rather, they can also be integrated as qualitative criteria. For instance, a requirement such as “the aeroplane should present desirable stability and control characteristics”, even if not providing a quantitative limit, can be taken into account so the designer can generate objective values attending to this criterion, or as a general design guideline.

8.5. Example Application Cases

In order to better illustrate the aforementioned procedure of the DECEX approach, two brief case studies are conducted in this section. These application examples shall focus on the main scope of the research, which is on conceptual design aspects for RPA. In particular, it is proposed that a design methodology is sought to be derived, using regulations from international stakeholders, for two distinct categories of RPA: in the first

case study, a civil tactical RPA, and in the second one, a HALE RPA. This allows to provide different perspectives on the regulations required for each of the categories and the effect of certification constraints in the design space, tying with the aspects of airworthiness influence in the design space discussed in section 8.2.

In both cases, it is sought to investigate the development of a procedure to select the wing loading at take-off (W_{To}/S_w) and the take-off power-to-weight ratio (P_{To}/W_{To}) for propeller aircraft or the take-off thrust-to-weight ratio (T_{To}/W_{To}) for turbofan and turbojet aircraft. This design approach shall be based on the use of a matching diagram that compares both variables, with this type of design approach having been introduced beforehand in subsection 2.2.3. In this diagram, restrictions of certain point performances (such as cruise, climb, landing and stall) will be represented to identify the feasible region that complies with all requirements. Some of the restrictions, such as those related to take-off, landing and cruise conditions, are mostly based on performance requirements—for instance, the maximum landing run distance is usually provided as an initial specification, whereas others such as climb, and stall constraints can have a more direct influence of certification requirements. The matching diagram is a classical step of conceptual design methodologies, such as those of (7; 8; 9), and it has also been employed in recent research for RPAS (10; 84; 128), albeit without considering certification aspects, which is the main gap that the DECEX procedure would seek to cover. As the design methodology itself is not the main scope of this work, rather the procedure to populate it with airworthiness aspects, the underlying equations are not developed here. From an overall standpoint, the ones which have been used have been the ones of Roskam (8), complemented with some typical values obtained from the RPA database of this thesis..

8.5.1. Case Study 1: Tactical RPA

The first case study focuses on the initial sizing through a matching diagram of a civil fixed-wing single-piston engine RPAS within the tactical category. The expected *MTOM* range varies amongst references. Here, the classification of (6) is considered; therefore, the aircraft would have approximately between 150 and 500 kg of *MTOM*.

Starting with the DECEX workflow expounded in the previous section, the scope of the design approach has already been commented above, which is step 1. For step 2, the results from the survey conducted within chapter 3 of this thesis would be directly applicable due to the focus on international entities and the scope of the design approach being centred on the airframe itself. In step 3, it can be seen from the characteristics of the type of aircraft to be designed as well as its envisioned missions that the certified category would be the applicable one. Even if some operational scenarios could be conducted within the specific category, since it is envisioned, that certain missions would require certification, the most conservative case is selected. Moving on to step 4, and knowing that the certified category is the one of application, Table 3-3 and Table 3-4. are used to seek the main documents to be considered here. In this case, the main certification

code available for civil RPAS of this type would be CS-UAS from JARUS, as the EASA paradigm is still under development. Thereby, this reference is selected as the main document. Then, for step 5, CS-UAS explicitly recommends the use of CS-LUAS as ADS. Since that document is applicable for below 750 kg, it can be used for this type of design methodology, so it is integrated as a priority 2 document. As no further specific documents are referenced by CS-UAS, step 6 is undertaken next. Here, the selection of documents is much more flexible as it is not required that it is explicitly stated by the main one. In order to complete the set of documents, it is decided to include, from the civil RPAS domain, SC-RPAS.SubpartB-01 on the side of EASA, and from the military RPAS domain, NATO AEP-4671, which is explicitly applicable to the *MTOM* range of interest. Finally, in order to compare the results with the manned aviation domain and to account for a reference from that field, which is much more established and mature than that of RPA, the legacy CS-VLA of EASA, which has a high level of specificity and also fits within the weight range, is also considered.

Moving on to step 7, the main variables of interest of the design methodology are defined. Attending to typical constraints for the matching diagram approach and, for this example, focusing particularly on certification-driven aspects, the following aspects shall be analysed: stall/minimum speed, V_{so} , climb gradient, γ , rate of climb, V_a , positive limit load manoeuvring factor, n_{lim+} , and gust intensity at design cruising speed, U_c . All of these can be represented in the aforementioned matching diagram as restrictions in order to determine the feasible regions of (W_{TO}/S_w) and (P_{TO}/W_{TO}) . Considering these variables and now proceeding to examine the regulatory documents for requirements related to them, this would constitute step 8, which results in the information presented in Table 8-3, where the level of specificity of each requirement has been indicated.

Table 8-3: Results summary of DECEX procedure application for the first case study, focused on a tactical RPA

Code	Stall Speed (V_{so})	Climb Gradient (γ)	Rate of Climb (V_a)	Load Factor (n_{lim+})	Gust Intensity (U_c)
CS-UAS	2110: M	2120: M	2120: M	N/A (refers to ADS)	N/A (refers to ADS)
CS-LUAS	N/A	53: M ^a	N/A	337: $n_{lim+} \geq 3.8$	333: 15.24 m/s
SC-RPAS. SubpartB-01	49: M	N/A	65: ≥ 2 m/s	N/A	N/A
AEP-4671	49: M	65: ≥ 5 %	N/A	337: $n_{lim+} \geq 3.8$	333: ≥ 15.24 m/s
CS-VLA	49: $V_{so} \leq 83$ km/h	N/A	65: ≥ 2 m/s	337: $n_{lim+} \geq 3.8$	333: 15.24 m/s

N/A: not available, **M:** Medium specificity. For High level of specificity, the limit values are declared. **a:** Limit values to be determined in accordance with the Authority, but none stated directly in the regulation.

One of the first conclusions that can be deduced from the table is the necessity of evaluating the level of specificity at the requirement level and not only at the document-

level. For instance, CS-LUAS, within Table 3-3, was quoted as having an overall high level of specificity. However, it can be seen that, depending on the requirement, a high level of specificity is not always found at the requirement level. Furthermore, one aspect that was mentioned in subsection 3.5.2 but was not demonstrated there is that the level of specificity at the requirement level for similar aspects, but within different regulations, can be significantly different. This can be seen, for instance, for the climb gradient, where for CS-UAS and CS-LUAS the specificity is medium and no particular limitation is declared, but for the NATO AEP-4671, a high level can be found. Through the DECEX approach, by checking the different variables of interest through various documents, the gaps can be filled with higher specificity requirements. For instance, in CS-UAS, for stall speed, the regulation states that *"The minimum safe speed must be determined..."*, but no specific threshold is established. The applicant, upon checking CS-VLA, could select that value as a design standard, and it can be proposed as a means to demonstrate compliance with the guidelines of CS-UAS by establishing a quantitative limit that is substantiated by another regulation. This can also provide aid when meeting the Authority to validate the certification basis and proof of compliance methods.

As the table has resulted in a high level of specificity being obtained for each requirement through the use of the different regulations, in step 9 it can be assumed that the objectives have been attained; therefore, when moving on to step 10, all of them can be integrated as quantitative restrictions in the design methodology. At this point, it is sought to demonstrate the relevance of the certification constraints, and thus of the DECEX procedure, in the determination of the feasible design space within the scope of this design case, when compared with the same case study but without accounting for these airworthiness aspects. On the one hand, some restrictions that are mainly focused on performance requirements instead of certification requirements are defined. These shall be take-off, landing and cruise restrictions. On the other hand, the restrictions related with the relevant airworthiness variables, with the limit values provided by the DECEX applications, are also represented. These shall be climb, gust and stall restrictions. A manoeuvring restriction has not been plotted, as tactical RPA typically develop surveillance and reconnaissance missions where no high-performance manoeuvres are expected to be performed. Again, the mathematical procedure as well as typical values can be found in the previously cited references. The resulting matching diagram is presented in Figure 8-3.

As it can be seen from the results of the case study and coinciding with the discussion on the influence of certification constraints in the design space of section 8.2, there is a noteworthy reduction in the design space when seeking to address the airworthiness restrictions extracted with DECEX, particularly through the climb and gust constraints. The great effect of the climb requirements can be explained through the use of a fixed landing gear of most tactical RPAS, which results in high drag, thus greatly penalising climb performance. Some of these restrictions were taken from codes that are not within the main level of priority of the DECEX corpus of documents—for instance, CS-VLA, which

is a code for manned aviation. However, by applying these restrictions as ADS, the designer can have a greater assurance in the certifiability of the system, rather than if an arbitrary value for the climb gradient, for instance, is decided by the applicant in view of the low level of specificity of the main applicable regulations (CS-UAS and CS-LUAS), which do not set a specific limitation. Constraining the design to the region considering airworthiness constraints leaves less design flexibility and might result in a more costly design (for instance, due to the higher power-to-weight ratio); however, it provides the advantages of certifiability and safety, which are the main topics covered in this research, and the main advantages provided by the use of DECEX in the development of design methods, as demonstrated here.

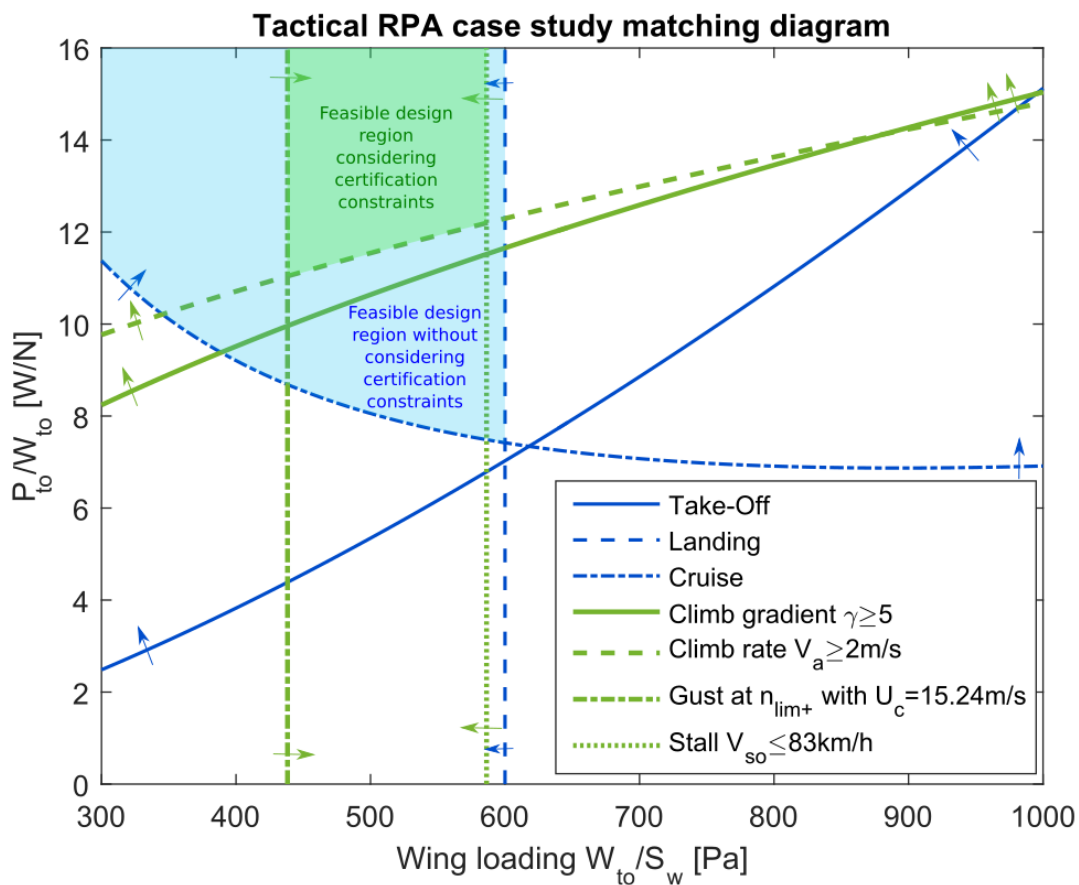


Figure 8-3. Matching diagram for the first case study, considering the restrictions mentioned in the main text. Constraints mainly related with performance initial specifications are in blue, and those related to certification aspects are in green. The arrows indicate where the feasible design region lies for each of the constraints. The feasible design regions with and without considering certification constraints are identified.

8.5.2. Study 2: HALE RPA

The second case study focuses on the initial sizing through a matching diagram of a fixed-wing single turbofan engine RPAS within the HALE category. These aircraft usually operate at very high altitudes over 50,000 ft (12,000 m) (6). A typical example is the

Global Hawk, with an MTOM of around 13,000 kg, resulting in very different characteristics from those of the previous case study.

As the workflow of the DECEX methodology has already been followed in more detail in the first case study, in the current one, these explanations are omitted in order to directly discuss the results. Firstly, the table resulting from step 8 in the workflow is provided in Table 8-4. It should be noted that, in this case, due to the aircraft's characteristics, it is only compatible with the applicability scope of very few regulations. It should be noted that the Part/CS-25 regulations have been considered here, which is according to the manned aviation regulation equivalency provided in the EASA Policy E.Y013-01 for typical HALE RPAS, including the Global Hawk (132). However, in these cases, a certain tailoring of the code would be required to adapt it to the characteristics of the RPAS, according to the aforementioned Policy. For instance, in this case, the original Part/CS-25 requires a minimum of two engines, so this aspect would have to be adapted to the RPA of study, which has only one engine but—according to the impact energy criterion of the Policy— would be certified with Part/CS-25. In any case, the primary regulation here would be the NATO AEP-4671

Table 8-4. Results summary of DECEX procedure application for the second case study, focused on a HALE RPA.

Code	Climb Gradient γ (LG Retracted)	Climb Gradient γ (LG Extended)	Load Factor n_{lim+}	Gust Intensity U_c
AEP-4671	65: $\geq 5\%$	65: $\geq 2.5\%$	337: $n_{lim+} \geq 2.72^a$	333: $\geq 10.29\text{ m/s}^b$
Part/CS-25	See note c	119: $\geq 3.2\%$ ^d	337: $n_{lim+} \geq 2.72^a$	See note e

a: As obtained from the mathematical expression given in the regulations for an MTOM of 13,000 kg. **b:** As obtained from the gust intensity values accounting for a strategic surveillance mission altitude of 12,000 m. **c:** The conditions for LG retracted provided in different paragraphs of the regulation pertaining to the flight path and climb conditions depend on the number of engines, and no explicit option is provided for one engine. Nevertheless, they are all much less restrictive than the one provided by AEP-4671. **d:** The only condition provided by the regulation for All Engines Operating and LG extended is that of balked landing, which has been considered here. **e:** Not applicable, as the gust envelope is not present in amendments to the regulations after the year 2000, and the method for complying with gust requirements is not directly comparable to that of the gust envelope, as provided in AEP-4671, which is the main code in this application of DECEX.

First of all, it should be noted that in this example, contrary to the previous case study, there are no issues of low level of specificity in the requirements, mainly due to both regulations being very detailed codes for aircraft with a comparatively high risk, which tend to have more specificity. Some of the conditions evaluated in the previous case study, such as stall speed and rate of climb, were not found in the codes of the current application case, thereby no airworthiness restrictions are considered for them here. Another difference of this case is that here some of the regulatory requirements when contrasting the different regulations present differing limit values, particularly the climb gradient with LG extended. These shall be compared in the matching diagram, which is presented in Figure 8-4.

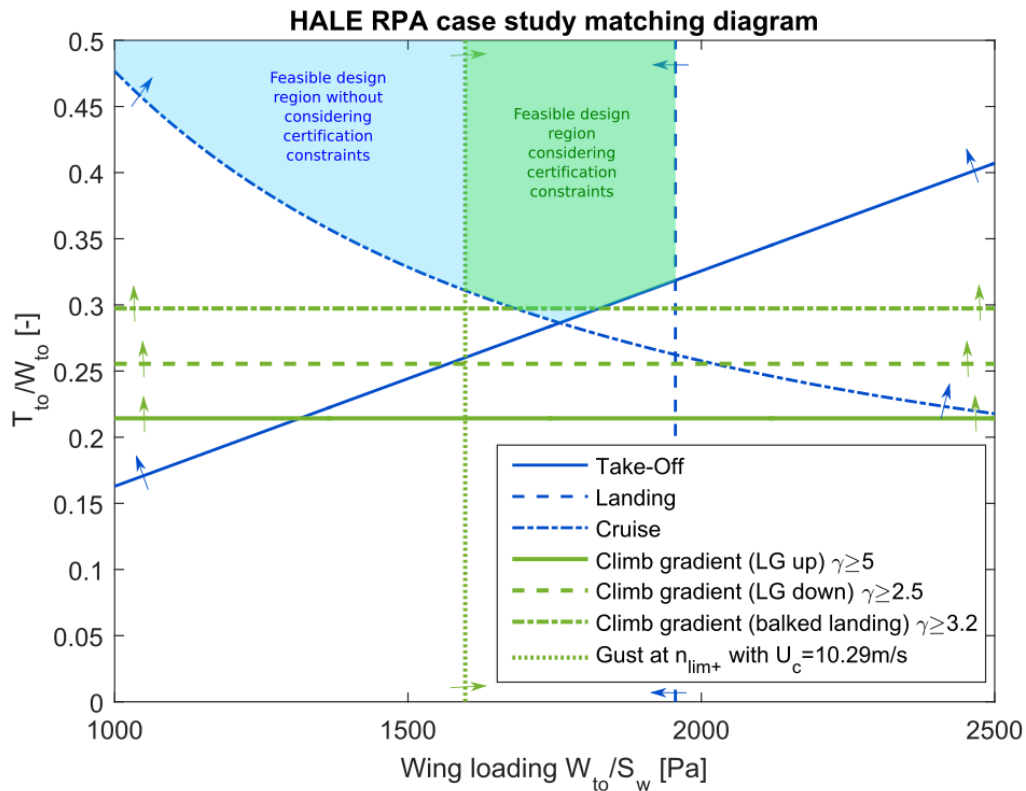


Figure 8-4. Matching diagram for the second case study, considering the restrictions mentioned in the main text. Constraints mainly related with performance initial specifications are in blue, and those related to certification aspects are in green. The arrows indicate where the feasible design region lies for each of the constraints. The feasible design regions with and without considering certification constraints are identified.

In this case study, it is seen that the influence of airworthiness restrictions in the design space, albeit present, is not as noteworthy as in the tactical RPA case, particularly since the design point is usually selected at high wing loadings and low thrust-to-weight ratios. This highlights that the relative influence of certification constraints in the design space can be very dependent on the scope of the design method, which not only includes the type of aircraft but also, through the application of DECEX, the considered regulations. This underlines the relevance of making the DECEX procedure flexible and adaptable to different scopes of design methodologies, as it can be seen that the influence of certification aspects can differ depending on the case. For this application example and going back to the aforementioned discrepancies in the values of the LG down climb restrictions, it is seen that the one provided by Part/CS-25 is more restrictive than the others. This can be explained not only by the gradient being more demanding than the one provided by NATO AEP for LG down but also since it is a baulked landing condition; thus, full thrust is not available from the start, which has been accounted for in the calculations. In any case, as these are not the primary regulations considered within the DECEX workflow, and the NATO AEP code already provides a high level of specificity, this restriction could be ignored, depending on the certification prospects that are sought by

the designer. Nevertheless, it still provides a relevant case of comparison between the manned and RPA airworthiness requirements and how they compare to each other.

8.6. Summary and conclusions

The DECEX procedure is the foremost contribution of this chapter. It has been developed with OBJ.3.2 of the thesis in mind and particularly with the purpose of allowing to integrate airworthiness requirements in distinct design methodologies through its application to each case. The main benefits that can be leveraged from its use can be summarised as follows:

- 1) The procedure provides a streamlined way to compare the similarities and differences amongst regulatory requirements from different regulations within the scope of the design method, as it was demonstrated particularly in the second case study when contrasting conditions and values for climb gradient were found.
- 2) It allows users to solve specificity gaps in main regulations by evaluating other, more detailed regulations from different entities and aviation paradigms. This was demonstrated particularly in case study 1, where a limit value for rate of climb was found in SC-RPAS.SubpartB-01 and CS-VLA, whereas the other regulations provided no explicit restrictions.
- 3) Its flexibility allows to populate design methodologies that have different scopes with regulatory requirements from diverse regulations. This was seen through the two case studies, each for a different category of RPA (tactical and HALE), thus resulting in distinct regulations to be considered.
- 4) It enables contrasting the effect of airworthiness restrictions on the design space when compared to the case of only considering initial specification requirements. In both case studies, the design space is reduced when considering certifiability, albeit the impact of airworthiness aspects was different in each of them.
- 5) The characteristics of flexibility and adaptability of DECEX allow it to be applied to a variety of regulatory landscapes and design methodology scopes, which is a necessity in the field of RPAS due to the aforementioned heterogeneity in regulations, the fact that rulemaking is still in progress and regulations are to be updated, and the novel design concepts that are usually developed in this area.

With respect to future work, albeit the review has focused on the main international, EU and USA regulations of RPAS, the market of RPAS is expanding worldwide. As such, the tools and procedures proposed in this research could be used for future analyses in other contexts, such as the thriving RPAS markets of Asia or Africa, or even to compare different national regulations as in previous works but using the novel criteria for consideration of design integration aspects. It is noteworthy that the review criteria used here, and the results can serve as a basis for future comparative work between other regulatory

documents. and the results can serve as a basis for future comparative work between other regulatory documents, which can further highlight the challenges in this area. Finally, the flexibility of the DECEX procedure could lend itself to further application, not only in different regulatory paradigms but also for design approaches with differing scope. Albeit the preliminary design stage is outside the scope of this thesis, the DECEX process has been developed with the possibility of applying it to methodologies with varying scopes. In this potential line of work, a more detailed review of structural considerations in the international paradigm could be evaluated in order to integrate them in an optimisation process. This application case could be leveraged for simplified structural design criteria, amongst other options. Another possible future application, which could be more directed towards further design phases, could be for a systems engineering approach once the main airframe has been sized. Other documents, more specific to systems engineering and safety analysis, could be integrated and compared through the procedure

Finally, it is noted that the two case studies developed here have not yet explored the design scope of small RPA. This shall be addressed in chapter 10, where the combined initial sizing approach derived from the three distinct chapters of this part of the thesis will be proposed. Overall, it is expected that this procedure can be employed in future work along with its capability to be coupled with the results of alternative surveys in order to further explore the joint airworthiness and design challenges in the area of RPAS.

9. MULTI-ROLE RPA CONCEPTUAL DESIGN APPROACH BASED ON INTEGRAL PERFORMANCE

The main topic of this chapter is the development of the third and final conceptual design approach as proposed within chapter 6. As seen back in chapter 1, one of the key characteristics of RPA, which is being increasingly emphasised by manufacturers and in their operational use, is the potential for the same air vehicle to develop a large variety of distinct missions (6) (35) (36). These individual operations may show significant differences not only in the payload mass which is being carried and in the target range or endurance, but also in the segments of the flight profile, the flight laws used to navigate the aircraft along the flight, and other aspects (27). At the synthesis level, the different missions that the envisioned aircraft is expected to be able to accomplish, as stated in the initial specifications, should all be considered concurrently, to ensure that the RPA resulting from the design process verifies these requirements.

In contrast, classic integral performance-based methodologies often employed for manned aeroplane conceptual design usually only take into account a single design mission to size the aircraft. However, for multi-role RPA, the aircraft should be developed taking into account all of the different design missions, with each of them having potentially very distinct characteristics regarding payload, flight profile, and flight law, among other aspects. Furthermore, there are other considerations which link to integral performance modelling that should be revised for the case of RPA, such as the type of drag polar model to be used, or the validity of certain hypotheses such as assuming constant propeller efficiency.

In view of the above, firstly, performance estimation methodologies for analysis should be revisited to evaluate their applicability and potential necessary adaptations for RPA, so as to then develop new synthesis methodologies that integrate the above-mentioned models towards the design of multi-role aircraft. To accomplish this, the research developed here shall examine the integral performance problem both from an analysis and synthesis perspective, connecting with those concepts which were introduced in subsection 2.1.1. These are the main guiding principles and purposes permeating the development within this chapter, whose final objective is to propose new physical-mathematical methodologies for analysis and synthesis of multi-role RPA at the conceptual design stage, being aligned with OBJ.3.3 of the thesis. The main structure of the chapter and the connections among its different points shall be expounded along of the introductory section that follows.

9.1. Chapter introduction, overview and structure

The potential of RPAS to carry out a wide array of missions is among their most promising features. These aircraft can develop operations of very different kinds, such as Intelligence, Surveillance and Reconnaissance (ISR), Search and Rescue (SAR), cargo transportation, communications relay, pipeline monitoring, etc (1; 6; 27). In addition, within reputable data sources such as the Jane's Yearbook (37; 389), it can be seen that many RPAs are labelled with the term "Multi-mission", which means that the same air vehicle can be used for an array of diverse applications. In these cases, the RPA usually performs missions of varied nature in different sorties (6). For example, the same aircraft could be used for both ISR and cargo transportation missions. This is usually achieved via changing the payload equipped in the air vehicle. This multi-mission nature of RPA that are already in operation has also been assessed by previous works compiling databases of these aircraft (35; 36).

Albeit the adaptability of the same platform to different missions is one of the most promising prospects of RPAS, it also constitutes a key challenge towards the development of models which can analyse this higher-dimensionality mission space, as it was brought forward in advance within section 1.3. As a comparison, when studying the space of potential missions for an existing aeroplane in the field of manned transport category aircraft, the mission is usually defined through two parameters: payload, PL , and range, R . In these cases, the aeroplane is generally assumed to fly at a typical altitude, h , and cruise Mach number, M , for all missions, and its performance through the mission space, as well as the boundaries of the operations which it can accomplish, are analysed with these hypotheses. This allows to draw the Payload-Range (PL-R) envelope of the aircraft for a given flight profile and flight law (7; 251). This diagram represents the performance of the aeroplane when varying the mission parameters, in this case, PL and R . Some studies also consider a variation in the flight speed, which results in different performances and limitations, thus giving a family of PL-R diagrams while again keeping the same flight profile and law (7; 404).

However, owing to the remarkable variety in mission types within the realm of RPAS, the degrees of freedom that have to be considered when studying their potential operations can potentially be higher than the above-mentioned variations that are usually the focus in the field of transport manned aeroplanes (17). The main reason for this difference is that the air transport aircraft, which is the main scope of most performance and design works in the academic literature, mainly conducts one type of mission: passenger/cargo transport. In contrast, it is usual that a single RPA can conduct operations of very different nature, as commented earlier (ISR, SAR, cargo, communication relay, etc.). This leads to a much broader mission space for these aircraft, which may not be satisfactorily modelled only by changes in the values of PL , R , and even flight speed, V . For instance, depending on the kinds of mission considered, not only different payload types might be required, but the flight law to be used (for instance, either constant speed or constant angle of

attack), and even the flight profile itself, might both show significant differences between one mission and another. These additional dimensions of variation should be taken into account when studying the mission envelope for these aircraft. It is noted that a similar problem can be found in certain manned aeroplane types which also have a larger mission variety, such as military aircraft (8; 11).

As an example comparison, an ISR mission is usually defined by a high target endurance over an area or path of interest, which is usually located at a certain distance from the launch point (6). However, a cargo delivery mission seeks to deliver a payload at a certain distance, and here the relevant point of interest for the mission is the landing point itself. In these two examples, it can be seen that the first is defined in terms of endurance, while the second is established through a target range value. Furthermore, the first requires an ingress flight to the place where the mission is conducted and then an egress stage back to the base, while in the second case, this concept would not be applicable, as the aircraft would always be advancing towards the mission objective point. This example shows in a simplified manner the many variations and degrees of freedom that RPA missions can showcase. Overall, in the open literature, the diversity of RPAS missions, operational scenarios, and flight conditions, along with their differences with respect to those of manned aircraft, have been noted to constitute a relevant hurdle, requiring the development of new performance analysis and sizing algorithms for RPA (17; 35).

In order to study, for a given RPA, the missions that it can accomplish, as well as the variables related to the development and outcome of each mission, an integral performance model is required. The aforementioned variables that are sought include some such as Trip Fuel (TF) consumed along the whole mission, or the variation history of different variables along the flight, such as the changes in lift coefficient, C_L , or engine rotational speed, Ω_E , along the flight. These models relate through differential equations the change in mass of the aircraft (which is, in most cases, the fuel consumed) with the range or endurance that it can achieve under specified conditions. These physical-mathematical models are commonplace in the area of flight mechanics (405; 406; 407), and are also used in aircraft design references for performance evaluation of a design which has been previously synthesised, in order to check its mission capabilities and whether it complies with the initial specifications laid out at the start. The aforementioned PL-R diagram is a particularly useful graphical representation of the mission space of an aircraft. It shows the feasible intervals of range that can be flown with each PL value, thus serving as an approach to visualise the envelope of feasible missions.

Considering the practicality of these integral performance models to analyse the array of missions that can be flown by a given aircraft, the first objective within this chapter, which is focused on mission aspects of RPA, shall be to examine the theoretical foundation of these approaches and analyse the current state-of-the-art for models of these kind. Upon conducting this assessment, and considering, as it has been done through this research, the particularities of RPA regarding their mission variety and some other aspects which

may not be compatible with the classical hypotheses, a new mission analysis model for fixed-wing RPA shall be developed. In particular, its scope shall be focused on reciprocating engine RPA, since they have shown to be the most sizeable powerplant group both within the database studies conducted in chapter 7 of this thesis, as well as in previous works conducting an statistical analysis on existing RPAS (36; 39). Thus, this would allow the developed model to achieve a higher range of applicability in the current existing RPA landscape, which is one of the main purposes of GDM design approaches such as the ones that are sought to be developed in this thesis. Other aspects related to the scope of the model shall be commented further below in this chapter.

Along the previous paragraphs, the discussion has focused on the performance estimations for an aircraft for which a definition of its characteristics – at least up to a certain extent – are available. This constitutes an analysis approach, according to subsection 2.1.1, as the inputs of the model include the geometric and physical characteristics of the aeroplane. However, the main purpose of this thesis is the development of design methods for RPA, which are synthesis approaches. In this latter case, the inputs would be the missions that the aircraft needs to accomplish, and the output would be the conceptual definition of a RPA which can accomplish those missions. Nevertheless, as commented in subsection 2.1.1, usually analyses models are required to develop synthesis approaches from their formulations. Therefore, the next step would be to develop an initial sizing procedure which leverages the proposed new integral performance method for RPA commented along the previous paragraphs. The key is to exploit the capabilities of the analysis model so that it can be used for sizing of multi-role RPA, as per the main objective of this chapter.

At this point, some comments shall be made on key terms that are to be employed through this chapter. These relate to notions including “off-design capabilities”, “multi-mission aircraft” and “multi-role aircraft”, among others. The definitions of these concepts and the differences between them vary along different references within the open literature (9; 408; 409; 410; 411). Therefore, it is relevant to clarify the meanings employed herein:

- **Design mission(s):** in this text, these are considered as those operations that are part of the design initial specifications and with which the final product must comply. Thereby, the design missions are the ones employed for the sizing of the aircraft, which is aligned with the definition of this concept of previous works, where often the notion of design point is also used (7; 8; 9; 17; 412; 413; 414; 415). Most of these investigations have considered a single design mission in their methodologies.
- **Off-design missions/capabilities:** once the aircraft has been sized according to its design mission(s), it is clear that it will also be able to perform other operations aside from those which were envisioned in the synthesis process. These are “off-design missions”. Thus, “Off-design capabilities” are defined here as the performance characteristics in relation to potential operations which were not

part of the initial sizing requirements of the aircraft, but which may be of interest towards potential operators when considering further applications than those which were taken into account during sizing (9; 17; 114; 260; 413). It is usual that off-design missions have performances that are sub-optimal when compared to the design missions(s), but they can nevertheless constitute valuable applications for the operators depending on the commercial applications which they are seeking (9; 404). It is even highlighted that the aircraft's performance capabilities on off-design missions could result in a competitive advantage over other models with worse performance outside the design mission(s) (9). The evaluation of off-design capabilities includes the study of the envelope of missions which the aircraft can accomplish, for instance, as represented through a PL-R diagram (410), as well as the quantification of figures of merit such as the *TF* consumed during each of the off-design missions of interest (410; 413).

- **Single-role vs multi-role aircraft:** in this thesis, this distinction is made depending on the number of design missions employed when sizing an aircraft during the synthesis process, and regardless of the other potential off-design operations that it can accomplish beyond those considered during its development. Therefore, a "Multi-role" aircraft or RPA is one that has been explicitly sized according to requirements pertaining to different missions to be accomplished by the same air vehicle (9), as opposed to a "single-role" aircraft, for which only one design mission employed in the sizing process.
- **Multi-mission aircraft:** in this work, this term is used as a generalisation when referring to the capability of an aircraft to accomplish diverse missions, either at the design stage or during their service life. This concept is most usually found in the literature when an aircraft, particularly a RPA, is marketed as being "multi-mission" (37), as commented earlier. In many cases, it is not known whether the different operations that an aircraft can accomplish were established during the synthesis process as design missions, or rather they are promising off-design capabilities. Therefore, this term is used in this thesis as an encompassing notion which covers both possible cases.

Figure 9-1 illustrates a conceptual representation of the comparison between the aforementioned notions, highlighting the differences between the analysis and design stages and perspectives. It should be noted that the distinction between the design mission performance and the off-design capabilities of different aircraft has been at the forefront of previous research in aircraft design (114; 404; 412; 413; 416). Some of these works have also analysed the conflicting decision of whether to size an aircraft for a larger variety of missions, which are then usually accomplished less efficiently; versus sizing it just for the envisioned design mission(s), typically resulting in a higher efficiency, at the cost of mission flexibility. In any case, analysing the off-design capabilities of an aircraft is

considered as an advantageous prospect both at the design and the operational stages (17).

Various references both from the fields manned and unmanned aircraft design have highlighted that multi-role aircraft present several potential benefits, ranging from mission flexibility and adaptability, to potential economic advantages (6; 9; 413; 417). However, in order to fully exploit the multi-role potential of RPA, this capability has to be considered from the first stages of the design process of the air vehicle, in order to ensure that the resulting aircraft can effectively accomplish all of the envisioned operations, which may have very distinct characteristics. Mission specifications are a key part of the initial requirements that are established at the onset of the design process, and they have an outstanding influence on the resulting aircraft concept even during the first design phases (9; 11). In particular, integral performance requirements from the design mission(s) have a crucial influence in the initial design weights estimation (8; 11; 413), which in turn is essential towards other design aspects such as geometric sizing. Therefore, if multiple design missions are sought to be considered, they should all be taken into account in the initial mission specifications and thus from the beginning of the design process, starting with the conceptual design phase.

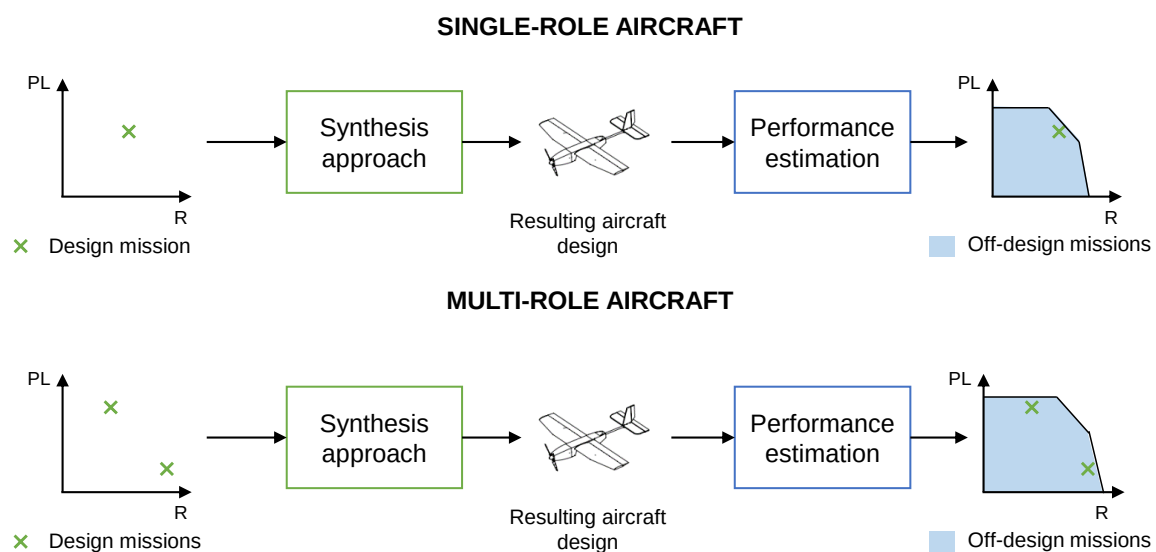


Figure 9-1. Conceptual representation of the difference between a single-role and multi-role aircraft, both with a similar set of off-design missions defined through the PL-R envelope, but with distinct design missions which have been used to size the aircraft.

Among the different topical areas covered in the overall review of section 2.2, the integral performance-based design one would cover the design considerations which are of interest here. As commented in the aforementioned section, the main purpose of these methods is to use the requirements related to mission performance to carry out a first estimation of relevant design variables, including key aircraft mass characteristics such as Maximum Fuel Mass (MFM) and MTOM. Some of the methodologies of this kind that

have been used beforehand for RPA design were listed in Table 2-2 and an overview of their main features and gaps was given in that chapter, but they will be revisited here in more detail.

In particular, some areas of potential improvement were detected when scrutinising the integral performance methods used in recent works within the RPA design literature. These gaps were mostly related to the lack of a larger flexibility in the flight performance models, which would be necessary to consider a larger array of possible variations in different mission parameters, such as flight law and flight profile changes between distinct operations. Furthermore, another remarkable gap which links with the main topics of this thesis is the current lack of multi-role initial sizing approaches for RPA, particularly in the conceptual design area. These aspects were also analysed in chapter 4, where it was seen that most RPA design environment functionality areas used methods from the manned aeroplane field, in spite of the differences between the missions carried out by each aircraft type. Thus, one of the main areas of future work towards the development of future RPA design packages was the consideration of a larger mission flexibility and also of multi-role capabilities, connecting with the trends of flexibility and RPAS that were analysed in that field. Therefore, the contents of this chapter and the main goals of the new methods to be proposed herein shall be aligned with addressing the aforementioned gaps.

In the same way as it was mentioned beforehand regarding the necessary adaptations and additional considerations for RPA analysis when compared with traditional integral performance estimation approaches, this also applies for the synthesis procedures based on those models. These RPA-specific adaptations are also key towards covering the aforementioned gaps which have been detected in the state-of-the-art. In order to cover the extraordinary variety of operations that RPA can accomplish, the initial sizing process should be able to accept requirements of various missions. Each of them might have their own flight profile geometry, flight law, and payload, as well as performance requirements related to either endurance or range. This would enable to propose a flexible approach that can be broadly applicable to many different missions of RPA, and which would allow to conduct the conceptual design of multi-role fixed-wing aircraft, as it is one of the main objectives of this thesis. In order to be able to develop this synthesis approach, a flexible analysis model which can calculate the integral performance of many diverse missions for RPA is a must. Hence the relevance of developing the aforementioned integral performance analysis model, so as to then integrate it within this synthesis procedure, allowing to leverage its capabilities now from a design perspective.

Considering the above, the purpose of this chapter is two-fold, as it covers both the dimensions of analysis and synthesis methods, while also considering the aforementioned off-design and multi-role concepts:

- 1) The development of a **new analysis model for the integral performance estimation of RPA at the conceptual design stage**. This model shall be tailored

to cover the wide variability of potential RPA missions, which can be conducted following different flight profiles and employing distinct flight laws. Thus, this method will be able to explore a high dimensionality mission space, allowing a thorough analysis pertaining to the off-design performances of these aircraft.

- 2) The development of a **novel sizing approach for the synthesis of multi-role RPA**, which allows to design an air vehicle which can accomplish several design missions with distinct requirements. This synthesis methodology shall employ the aforementioned integral performance analysis model.

9.1.1. Objectives and scope of the models

From a broad perspective, and considering both the current gaps in state-of-the-art approaches and also the scope and purpose of the thesis, a series of guiding objectives for the analysis and synthesis methods to be developed in the current chapter can be formulated:

- Both of the approaches shall be compatible with a **high degree of flexibility of the mission definition**, considering various dimensions of variation: PL, R or E, flight profile segments, flight law, etc. This will allow the analysis process to study a larger variety of off-design missions, and the synthesis method to size the aircraft attending to operations which can be very distinct. This links with the method flexibility trend and the features associated with it as developed in chapter 4, and is one of the key points highlighted by previous works towards more expansive RPA performance studies (17; 35). Additionally, this aspect will enhance the applicability range of the methodology, which is according to the purpose of GDM design approaches.
- The design method shall **cover the design of various RPA layouts**. As commented through the thesis, the configuration diversity of these aircraft is one of the main challenges of this field, with previous research highlighting the need of new methods that consider the variety of RPA layouts (21). This was also considered among the key areas for new RPA design packages in chapter 4, which was then substantiated in chapter 7 when seeing that the usual layouts considered for RPA design show certain mismatches with the configurations that are most commonly seen in existing aircraft.
- The methodologies shall be aligned with the **needs of the conceptual design stage** in terms of the required volume of input data, calculation times, and accuracy levels. Thereby, the focus shall be on rapid methods which can be run in seconds or minutes in a personal computer. Furthermore, since the volume of data which is known of the aircraft at this point in the design continuum is low, the methods should be able to obtain reasonable estimates with few inputs, adhering to the type of variables analysed in the statistical methods of chapter 7.

Integral performance models, whether they are used for analysis or synthesis tasks, strongly depend on aspects such as the type of aircraft which is being analysed, the mission's characteristics, and the overall hypotheses that are considered. This is because these performance estimation approaches are at the same time dependent on the use of other modelisation aspects, such as the flight profile geometry, the considered flight laws, and even the drag polar model. As an example, if flight in the high-subsonic or supersonic regimes is considered, the drag polar model should include compressibility drag (251). Furthermore, albeit some mission profiles can represent with adequate accuracy several types of operations, other flight geometries might fall outside their modelling scope. For example, a classic profile of climb – cruise to destination – descent, would not be able to represent ISR or SAR missions where with ingress and egress segments to the destination point which have different flight laws to the one employed in the target area.

Thereby, there is a certain compromise between the scope of the model and its complexity. Albeit one of the goals stated above is to propose models with a high applicability range, this should also be balanced with a feasible level of intricacy, particularly when considering the adequacy of the methods for the conceptual design stage. Thereby, the focus shall be on the missions that are most commonly seen for RPAS, as well as on the most usual types of aircraft. Particularly, it must be noted that aeroplanes with reciprocating, jet, and electric powerplants all have distinct solutions of the differential equations of flight mechanics, so the model presents remarkable differences among these cases.

With this, some of the main aspects that set the scope of the methods to be developed here can be summarised in the following points. Further comments supporting these decisions shall be expounded along the chapter.

- The performance and design approaches shall focus on reciprocating powerplants. These are, by a significant amount, the most common in this field, as seen not only in the database compiled in chapter 7, but also in other RPA databases as seen in previous works (36; 39). Furthermore, it has been seen that the powerplant type can have a significant effect in correlations amongst certain RPA variables (39). Since a geometric sizing approach will also be needed, it is also necessary to adapt the applicability of both performance and geometric sizing methods so they are aligned. This also points towards focusing on the reciprocating engine category, as the statistical relationships extracted in chapter 7 were also obtained for this RPA type.
- As it will be thoroughly expounded through the chapter, the mission profile to be considered here will be a flexible one that includes: take-off, climb, ingress flight, mission stage, egress flight, approach and landing. The mathematical definition of the profile shall be done so that the ingress and egress stages can be neglected if needed. This flexible model covers most of the typical missions for Short and Medium Range (SMR) RPAS, including many ISR, cargo transportation, and SAR

operations, as well as being able to model others in the areas of environmental and scientific research (27; 418). It is also noted that SMR RPAS are also among the most prominent ones currently in service as seen in previous research (53; 116).

- Since the focus here is on performance aspects, and the design methodology seeks to conduct the initial definition of overall aircraft characteristics such as *MTOM*, *OEM*, and *S_w* among others, stability and control considerations would fall outside the scope of the methods to be proposed here. These aspects are usually considered at later steps of RPA design (35; 61), usually once an initial geometric sizing of the overall aircraft has been conducted, which is precisely the final purpose of the design procedure to be proposed here.

9.1.2. Contents overview and chapter structure

In view of all the above, this chapter covers the development of novel analysis and synthesis procedures for multi-role RPA conceptual design based on integral performances. Thus, both perspectives, as introduced in subsection 2.1.1 (where it was seen that they influence each other), shall be developed in parallel here. Firstly, an assessment will be conducted of integral performance models for analysis, and also of integral performance-based design methods. The particularities of RPA shall be taken into account to evaluate the applicability of the models used in previous state-of-the-art studies when addressing objective at hand, unveiling potential gaps. This literature review and model assessment is conducted in section 9.2.

With this, the adaptations and novel considerations to be considered in the methods proposed in this chapter will be expounded, and the development of both models shall be tackled, which is done in section 9.3. It should be mentioned at this point that, in order to close the mathematical problem of the synthesis approach, and aside from the newly-developed analysis procedure which is to be adapted for design purposes, other approaches shall be required. These include a geometric sizing process and a drag polar estimation methodology. The first of these two will be covered through the application of both of the sizing approaches based in empirical relationships that were developed in chapter 7, as it will be expounded in detail later. The drag polar model estimation method shall be adapted from proven approaches currently available in the literature, as it will be discussed later on in this chapter. It is anticipated that the synthesis method based on integral performances developed here also falls within the definition of an overall initial sizing approach as expounded in section 2.2, since with the combined aid of the chapter 7 statistical relationships, it allows to reach a first definition of the main elements of the aircraft's geometry, including its tail surfaces, which constitutes an original aspect when compared to current conceptual design procedures for RPA.

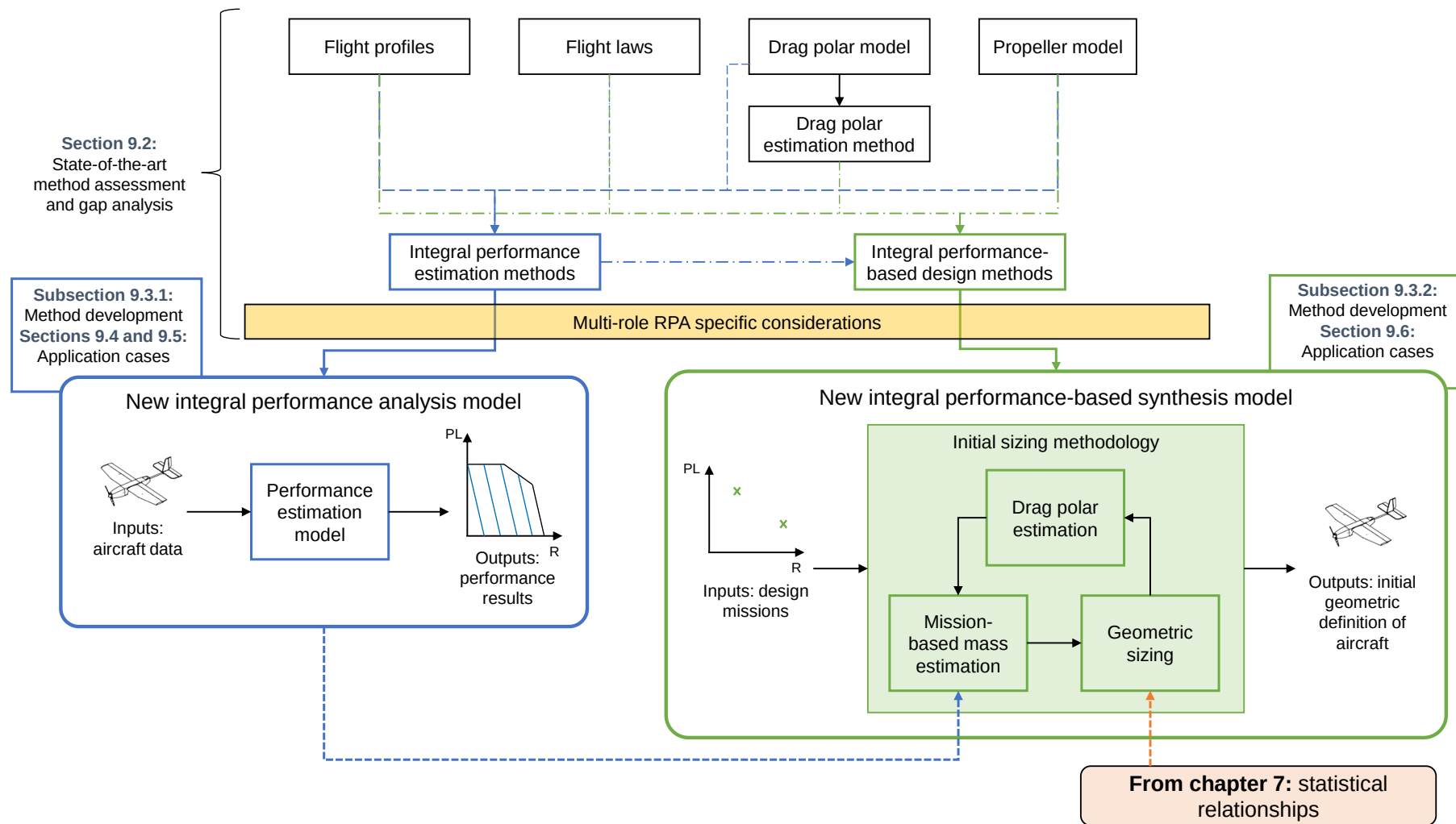


Figure 9-2. Conceptual map of the different models, as well as their connections, involved in the creation of the analysis and synthesis approaches based on integral performances developed within this chapter. The chart contains the sections where each step is expounded, as well as the connection with the statistical models developed in chapter 7.

Finally, the developed approaches are applied to a series of cases of study, which allow to showcase their capabilities and also to validate and quantify the errors of the methods. Applications of the integral performance analysis model are conducted in sections 9.4 and 9.5, whereas those of the design approach will be developed in section 9.6. Finally, section 9.7 includes the overall conclusions of this part of the thesis. Figure 9-2 provides a conceptual map which serves to summarise this introduction as well as the main elements to be covered along the development of this chapter in its different sections.

9.2. Research background and state-of-the-art analysis

This section provides an overview of theoretical aspects which form the basis of analysis and synthesis approaches related to the topical area of integral performance. For each of the subjects covered in this section, some comments shall be included with respect to the methodologies and models found within the state-of-the-art, with an emphasis on the differences that RPAS might entail in comparison to classic approaches pertaining to manned aircraft. Both analysis and synthesis considerations will be covered, since this chapter includes the development of novel approaches in both of these areas. The content of this section in terms of the models to be expounded here, the potential adaptations required for RPA which are identified, and the current gaps in state-of-the-art approaches will serve as a basis towards the development of the novel analysis and synthesis methods proposed in this research.

Aircraft integral flight performance is only one of the many areas of study of the discipline of flight mechanics (405). The purpose of integral flight performance estimation is to study the behaviour of the aircraft when considering a significant elapsed time along its flight. Consequently, it is mainly centred in analysing long phases of flight, such as cruise or loiter, which are the ones where the most amount of mission fuel is consumed. Under the aforementioned hypothesis of elapsed time, the mass change that the aeroplane suffers cannot be neglected, as the quantity of fuel consumed in long periods of time is significant. This is the main difference with the point performance methods and hypotheses. Integral performance models are mainly focused on the study of the range and endurance of an aircraft depending on its properties, flight conditions, and mass variation.

The objective of integral performance methods varies depending on whether they are used from an analysis or synthesis perspective:

- When used in **analysis calculations**, they allow to analyse the performance characteristics of an existing aircraft. This can be useful for studying other missions which can be performed by an aircraft that has already been designed beforehand.
- If employed following a **synthesis approach**, they can allow to estimate the aircraft's characteristics (for instance: *MTOM*, *MFM*, etc.) which allow it to comply

with its initial requirements, as these tend to include integral performance specifications (such as desired range or endurance when carrying a certain payload).

Within the open literature, the analysis of aeroplane integral performances presents slight differences depending on whether the approach of the text is more focused on flight mechanics analysis (405; 406; 407), or if it is more oriented towards design activities (1; 8; 9). The first references tend to perform a more thorough analysis of the different possible flight laws (constant speed, constant angle of attack, etc.), whereas those more focused on design usually assume simpler equations for performance modelling and different flight laws are not studied in as much detail. On the other hand, the first type of studies tend to leave the equations as a function of the initial and final weight of the cruise segment, whereas the second group of references usually relate these weights with overall relevant design and operational weights of the aeroplane, such as the Take-Off Weight (TOW), Operating Empty Weight (OEW), Fuel Weight (FW) carried for the full mission (FW), etc. This is usually done through a consideration of the full flight profile, with typical weight fractions being used for flight phases such as warm-up and initial climb, or for the reserves to be carried for a diversion flight. There are exceptions to this overall trend, such as studies that are more performance-driven but also study the complete flight profile and relate the initial and final weight of the cruise segment with overall design weights of the aircraft (407), and there are also references which are more focused on design that study various possible flight laws (9).

In this research, a combined approach is undertaken: different flight laws shall be considered, and with respect to the initial and final mass variables of the long phases of flight, these shall be related to the relevant design mass definitions. Furthermore, other segments of the flight will also be taken into account. With this, it is sought that the strengths of both approaches can be leveraged, since this research deals with both performance and design aspects. In particular, this combined approach is particularly relevant towards developing approaches that are valid and broadly applicable for RPA. This because, as mentioned beforehand, these aircraft can conduct a wide array of missions. Thus, adding more degrees of freedom and flexibility to the methodology allows to model a wider variety of these possible operations, therefore also enabling to design multi-role RPA that can cover many more mission types.

There are many different aspects and considerations which need to be modelised in both analysis and synthesis approaches related to integral performance. As illustrated in Figure 9-2, these kind of methods require the definition of a flight profile, the selection of a flight law (which will have a direct influence on the mathematical equations describing the performance model), the choice of a type of drag polar expression, and the use of one of various possible propeller models. The characteristics of the resulting integral performance approach shall depend on the decisions and hypotheses involved in all of these different aspects.

Thereby, RPA-specific considerations should be observed for each of these distinct subject areas, in order to ensure that the full model takes into account the singularities required to perform a satisfactory analysis and design of these aircraft. The way in which the characteristics and potential gaps of those aspects with a narrower scope affect the full approach that has a broader scope follows a similar process to the influence between the distinct topical areas of RPA design commented through chapters 2 and 6. Therefore, the first four of the following subsections shall focus on the background and state-of-the-art of each of the elements required to constitute the full performance models, so as to then analyse the scenario from an encompassing viewpoint in the final ones.

9.2.1. Mission flight profiles

The mission profile, at the conceptual design stage, consists of an idealised representation of the different flight phases to be conducted by the aircraft in a typical mission, as well as some of the conditions and hypothesis affecting each of these segments. The definition of the flight profile has a fundamental relevance in performance analysis, as it influences the governing equations for the integral performance estimation as well as the derivation of the payload-range and endurance-range diagrams, as it will be seen later.

Figure 9-3 illustrates two examples of mission profiles which have been widely employed within the state-of-the-art of aircraft conceptual design. **Mission profile A** is representative of a payload delivery mission at a certain range. It has mainly been employed, with some variations, for manned aircraft passenger transport missions in previous works, such as in (7; 8; 9; 251; 410; 413). This type of mission profile has also been employed in RPA performance analysis and initial sizing studies when focusing on payload delivery missions.

Other type of operations require different mission profiles towards their adequate modelisation. Missions such as ISR, and aerial monitoring or photography of a certain area, which are very common for RPA (1; 6; 53), can be more adequately represented through **mission profile B**. This one which contains three main segments representing a cruise-in (ingress) ingress flight to the mission area, then a loiter or inspection phase, and finally a cruise-back (egress) stage back to base. In each of the diagrams represented in Figure 9-3, the “mission segment” has been considered as the combination of phases where either the distance covered in them, or the time spent over an area of interest, actively contribute to the accomplishment of the overall mission. Within the scope of this research, it is considered that these two profiles allow to represent, at the conceptual stage, a majority of RPA operations of interest. Other mission profile variants, mainly applicable to military operations, which tend to present a wider spectrum of flight profiles, can be consulted in reference (263).

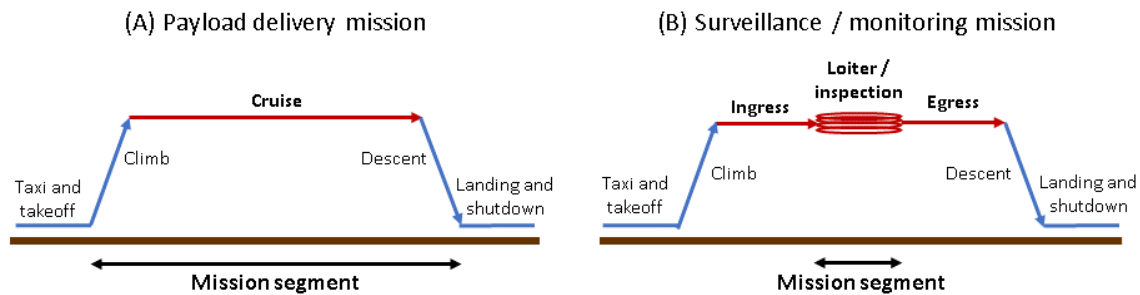


Figure 9-3. Representation of two notional flight profiles representative of distinct types of missions. The red arrows represent the “fuel intensive phases”, which are those in which the majority of the fuel is consumed, and thus the focus of integral performance methods.

It is seen that the mission profile depends on the nature of the operation which is being modelled. Therefore, considering the scope of the integral performance methods to be developed here, which are intended to represent a wide variety of RPA operations so that these approaches can be leveraged for multi-role RPA, a significant deal of attention must be given to the flight profile geometry and the flight laws employed at its different segments.

At the conceptual design stage, where simplified models for rapid performance calculation are the norm (7; 8; 9; 58), flight phases can be separated in two categories:

- **Fuel un-intensive phases:** where a comparatively low fuel fraction is consumed, and which are usually modelled through the use of a typical fuel ratio (8).
- **Fuel intensive phases:** where most of the block fuel is expended in a typical operation, and which are usually modelled through range or endurance equations derived attending to the flight laws used in each case (407).

It has been shown in previous works that, even for the climb phase, the fuel consumed during this stage is usually much lower than that which is used during cruise and ingress-egress phases. This is even true for aircraft with relatively long climb phases due to their operation at very high flight altitudes, as it has been calculated for various manned aircraft as well as for RPA (11; 407). Considering this, in Figure 9-3, only the phases pertaining to the main mission, ingress, and egress have been considered as fuel intensive, which is one of the main hypothesis governing the models presented in this chapter, as it has also been done in previous RPA research (117).

In order to complete the definition of a mission profile towards its use in flight performance methods, either for analysis or synthesis approaches, the flight laws of fuel intensive stages should be defined. These flight laws represent the physical and mathematical interpretation of the flight variables which are either maintained at fixed values or rather they are varying during the segment. For instance, a cruise flight can be conducted at constant airspeed and altitude, while varying the lift coefficient through the

angle attack as fuel is consumed; or it can be flown at constant airspeed and lift coefficient but with varying altitude – amongst other possible options (9). The use of one flight law or another has a direct effect on the equations governing range and endurance modelling, and thus this also impacts the payload-range and payload-endurance diagrams, as it will be seen later. Depending on the mission, type of aircraft, and ATM considerations, some flight laws might be preferred over the others. For instance, it is generally stated that flight at constant altitude is preferable from the perspective of ATM and possible flight space restrictions (7; 8). The way in which the flight law influences the integral performance equations and the PL-R diagram is further developed in subsection 9.2.4.

Finally, it should be highlighted that the mission profile could also include the flight phases of a contingency flight in the case that landing is not feasible at the envisioned location and the aircraft has to divert to another recovery spot (8; 419). However, this diversion flight would not be part of regular operations, and its main purpose is to model the reserve fuel that the aircraft is required to carry in order to be prepared for the case in which the contingency scenario occurs. However, at the conceptual design stage, instead of deriving the reserve fuel through the modelisation of the diversion flight profile, it is usual to estimate it through either empirical correlations obtained for similar aircraft (7), or by employing a typical ratio of reserve fuel with respect to the landing weight (58; 412). In RPA performance modelling at the conceptual stage, diversion flight is usually not considered within the mission profile definition (117; 420), and even in some cases reserve fuel itself is not accounted for in this stage (117). In this work, as it will be expounded in section 9.3, reserve fuel shall be estimated as a specified fraction of landing weight, which can be set as zero if no reserve fuel is considered.

Considering the above, it is seen that the flight profile is essential for accurate representation of the missions which are to be modelled by the performance model, with this subject matter also connecting with the topic of the flight laws and mission envelopes to be developed in 9.2.4. As seen within the review of chapter 2 in Table 2-2, most works in the topical area that is of application here are of the AADM type. Thereby, they tend to consider a single type of flight profile with a fixed geometry and numerical values corresponding to the mission to be developed by each of their specific RPA, with most of their modelisations fitting with mission profile B as illustrated earlier (25; 117; 121; 122). However, here the purpose is to develop a GDM method, so not only must the flight profile allow for variations in the features that define it so that it can be adapted to each design case (such as by changing the value of the distance associated to the ingress and egress segments), but it is also sought that it considers a larger mission variability. Thus, a flight profile definition which covers both types shown in Figure 9-3 shall be proposed in section 9.3.

9.2.2. Drag polar models and estimation methods

The drag polar is the mathematical representation of the relationship expressing the drag coefficient, C_D , as a function of the lift coefficient, C_L . This name comes from the fact that, if the scales of the drag and lift coefficients are the same, the points in the curve give in polar coordinates the magnitude and direction of the resultant aerodynamic force expressed as a dimensionless coefficient (406). A drag polar can be obtained for two-dimensional bodies such as aerofoils (for which the symbol C_d is usually used), for different aircraft components such as the wing or the fuselage (with the notation typically being C_{Df} for the fuselage, for instance), or for the full aircraft (indicated by C_D). The generic drag polar mathematical representation for the full aircraft, as well as its dependencies, are given by:

$$C_D = f(C_L, Re, M, \text{geometry, configuration}) \quad [9-1]$$

Where Re is the Reynolds number and M the Mach number, with the latter accounting for the compressibility effects. In the case of this thesis, where the focus is on RPA, and most of them fly at low-subsonic speeds (6; 53), as it was also seen in Figure 7-27 obtained from the database, compressibility effects can be neglected with minimal loss of applicability. In the above, “configuration” refers to the position of the flaps, whether the landing gear is extended or retracted, etc. (7), instead of to the overall layout of the aeroplane, which is the main meaning employed through the thesis.

There are several ways to obtain the drag polar, with differing applicability and suitability depending on the design phase. In the final stages of aircraft design or when the aircraft has already been manufactured, wind tunnel or flight tests can be conducted on the final aircraft layout, and an accurate representation of the polar can be obtained (8; 421). However, during most of the design process, the design is actively changing and evolving. In any case, it is critical to have models which can estimate the drag polar with adequate accuracy within each of the design phases so as to use them in performance estimations along the design process. In later design phases, when the design is already mature and refined, the use of CFD is commonplace. There are a broad array of resolving techniques and numerical methods, which have differing capabilities and limitations. An overview of some of these can be seen in reference (53). It is recognised that Reynolds Averaged Navier Stokes (RANS) techniques currently constitute the best compromise between being able to solve the flow around a full aircraft in an acceptable time, while having an adequate level of accuracy (53). However, certain phenomena such as streamlined body viscous lift-dependent drag and its dependency with angle of attack are not adequately captured with these approaches, and advanced but more computationally expensive methods such as Large Eddy Simulations (LES) have to be employed so as to achieve good similarity with experimental results (422).

For earlier design stages, it is of paramount importance to use models that can estimate the drag polar in a shorter amount of time, and more importantly, which require few input

data to perform an adequate estimation of the mathematical expression of the drag polar. The need of simplified and fast models that require a small array of input data for conceptual design was discussed in more detail in subsection 2.1.2. In the case of the drag polar estimation methods to be used at the early stages of design, it should be considered that at this point, only a few geometric parameters of the aircraft are known, as well as some representative flight conditions. Therefore, it is recognised both in classic references of aeroplane design as well as in more recent research works, some of which are devoted to the field of RP (10; 53; 115), that the most adequate model for drag polar estimation in the initial stages of conceptual design is one which is parametric, follows a semi-empirical approach, and where the coefficients depend on basic geometrical aspects of the aircraft's OML as well as on the flight conditions. As the aerodynamic surfaces become defined with a higher level of detail as the design progresses, this can be complemented with fast numerical aerodynamic approaches such as Vortex-Lattice or Doublet-Lattice methods.

Therefore, as the focus of this thesis is on initial sizing, a parametric semi-empirical model shall be employed here. For the drag polar estimation model to be practicable, it should be usable with a level of geometric definition akin to that corresponding to the output of the geometric sizing procedures proposed in chapter 7. The validity of such simplified manual-like drag polar models requiring few inputs for RPA conceptual design is supported by recent references in this field, some of which have developed their own models and compared the results of these rapid procedures with CFD and wind tunnel data, verifying a satisfactory agreement within the accepted error of conceptual design (61; 115). However, in most cases, the models used for manned aeroplane analysis and design require certain adaptations to be applicable to their use in RPA (52; 53), as it will be commented further below.

When representing the mathematical expression for the drag polar in the early design stages, a parabola curve is usually employed (51). This can come in two different forms, which are represented in the following equations:

$$C_D = C_{D_0} + C_{D_1}C_L + C_{D_2}C_L^2 = C_{D_0} + jC_L + kC_L^2 \quad [9-2]$$

$$C_D = C_{D_0} + C_{D_2}C_L^2 \quad [9-3]$$

The first expression retains all terms of the quadratic curve (two alternative notations are given), while the second is expressed with only two terms. Each has received various names along different literature references. For instance, in (51), the first one is named “three-term drag polar” and the second “two-term drag polar”, whereas in (9; 53), the first one is called “adjusted drag polar” and the second “quadratic drag polar”. In this thesis, the former naming convention is used. It is also noted that the symbols used for the terms also change between the distinct references.

The two-term polar is usually employed in many conceptual design approaches, since it is compatible with simplified analytical expressions for flight mechanics modelling, as it

will be seen in subsection 9.2.4. This approach is typical in the flight mechanics models used for synthesis approaches in classical design methodologies, both for manned aircraft (7; 8; 9), as well as for RPA (6; 10).

However, due to the cambered profiles used in the wing of many aircraft, among other effects, the true drag polar usually has a non-symmetrical relation with C_L (11; 51). Even in these cases, it is possible to use a two-term approximation which is close to the true polar in a region of interest, such as around the typical cruise lift coefficient, so that the error is minimised in the interval of most practical use. This approximation can be achieved through various means, such as by plotting the true drag polar and using a statistical fit considering the points around the typical cruise C_L range to obtain the expression of a two-term curve (7; 8), or through an analytical approach which establishes a shared point between the true and approximated polar curves, with the use of the minimum drag point being recommended (51).

Albeit the above-mentioned approximations provide remarkable results for most aircraft, some air vehicles intended for long endurance operations, such as many ISR missions, show a remarkably high camber of the profiles used in their wing (11). This leads to a noteworthy asymmetry of their true drag polar about the $C_L = 0$ axis. In these cases, the aforementioned approximation methods do not fit as well the original curve, with larger deviations occurring for small changes in C_L with respect to the interval used to generate the two-term approximations. In these cases, it would be recommended to use of a three-term drag polar such as the one shown in equation [9-2]. This polar model is also recommended when representing drag at transonic speeds, among other areas where it is more commonly used (51).

At this point, it is noted that many RPA would fall within the aforementioned scenario of their wing being built from profiles with a high camber. This is particularly true for ISR RPA, which is a very common type of mission for these aircraft (1; 6; 26; 27). A notable example is the RQ-4A Global-Hawk, whose drag polar shows a minimum around a value of $C_L = 0.3$ (11). This behaviour is also observed in smaller RPA, such as the KARI UAV, which was measured in a wind tunnel to obtain its true drag polar, with the minimum drag point being found at approximately $C_L = 0.4$ (423). This latter RPA shows characteristics which are comparable to many tactical ones, with this group being one of the most sizeable in the database compiled as part of the work of chapter 7. Therefore, the use of a three-term drag polar could be preferred for RPA analysis and design, even in the conceptual stage, so as to aid in obtaining more accurate and representative performance results. This type of polar has been used in previous research developing methods for the rapid estimation of RPA performance, giving good accuracy with respect to CFD results and wind tunnel measurements (115). However, its use is not too extended within this field, with most previous works using a two-term drag polar instead.

There is another reason to use the three-term drag polar for RPA, particularly within the research conducted in this chapter. As mentioned beforehand, the two-term

approximations obtained from the true drag polar have a satisfactory agreement with the original one around the point or area where the fit was conducted, which is usually selected around the typical operating values of C_L . However, as mentioned beforehand in this chapter, RPA tend to have a strong multi-mission nature. This could imply operations where the cruise values of C_L can be remarkably different from one another. Therefore, a two-term approximation that fits well around a certain value pertaining to a specific mission could then give a higher error for a distinct operation where the values of C_L are different. Considering that the methodologies developed in this chapter take into account a wide variety of possible design and operating missions, with possibly very different flight profiles and laws, it is key that the drag polar model has a satisfactory accuracy along a very wide range of values of C_L .

The reasons mentioned above substantiate the use of a three-term drag polar for this study. Therefore, and from the preceding discussion, it is required to select a suitable drag polar estimation method to estimate its coefficients as a function of the RPA geometry and flight conditions. Various references from the field of manned aircraft have proposed semi-empirical parametric models for polars compatible with more than two terms, as seen in (7; 8; 11; 54). However, as brought forward in advance in the introduction, previous research within the field of RPA has identified that the direct application of drag polar estimation methods originally developed for manned aircraft results in significant inaccuracies when applied to unmanned aircraft, with adaptations being required (52; 53). This is mostly due to the presence of bluff bodies in RPAS such as payloads, fixed landing gears, and antennas. Even in cases where these type of elements are considered in manned aircraft polar estimation approaches, the different characteristics that they show in RPAS leads to discrepancies in the drag estimation. Some previous works have sought to provide adaptations to the classic drag polar models so as to enhance the accuracy of these predictions for RPAS, with an emphasis on the lift-independent drag of bluff bodies such as those mentioned beforehand (424; 420).

Considering all of the above, and within the context of the research of this chapter, a three-term drag polar estimation approach including various drag contributions shall be employed. This approach shall be based on classic models for manned aeroplane design (7; 8; 11; 54), but it will also include adaptations for RPA drag estimation as provided in recent works (424; 420). Further details on the model shall be given in section 9.3.

9.2.3. Propeller analysis models

The study of propeller performance has been a key subject of study in aviation for a long time (425; 426). In a similar vein to drag polar estimation methods, there are various approaches for propeller performance modelisation, with each of them being more suited for different analysis and design endeavours depending on the computational resources and level of fidelity which are sought. These methods can be broadly considered in the following groups (427; 428):

- **Blade-modelled approaches:** these include the classic methods of momentum theory, blade element theory, and further improvements on them, such as for instance Goldstein's vortex theory (429). Their formulation stands on a physics-based approach, which in the case of more complex formulations is solved numerically. For blade element theory and its derived approaches, it is required to know the geometric definition of the propellers and the characteristics of its aerofoil. Their fidelity is generally considered low when compared to other methods (428).
- **Blade-resolved CFD approaches:** they are based on the solution of the fluid-dynamic equations via high-fidelity CFD approaches. A more detailed definition of the propeller is required to leverage the potential of these methods. Albeit their accuracy is higher, the computational cost is also noticeably increased.
- **Hybrid approaches:** some works have developed hybrid methods, for instance via the combination of a subrogate model based on CFD results with the blade element theory, as done in (428). It has been shown that this can provide an increase in fidelity without large penalties in computational time. However, most of these models do still require a more detailed knowledge of the propeller blade geometry.
- **Empirical approaches:** when wind tunnel data measurements of propeller performance are available, their empirical performance curves can then be employed to complement aeroplane performance methods. When integrating the propeller along with the rest of the airframe, interference effects produce certain variations with respect to the measured behaviour of the propeller. In spite of this, and as long as the propeller being used is the same that the one measured in the wind tunnel, the accuracy of using these empirical curves is satisfactory in methods such as the ones used in the first stages of aircraft design (9).

The main purpose of the different models outlined above is to obtain the variations in propeller performance as a function of its operating condition. This usually includes the changes in thrust coefficient, C_T , power coefficient, C_P , and propeller efficiency, η_P , as a function of the advance ratio, J . The related expressions that define these variables are given below:

$$J = \frac{V}{nD_p} \quad [9-4]$$

$$C_T = \frac{T_p}{\rho n^2 D_p^4} \quad [9-5]$$

$$C_P = \frac{P_p}{\rho n^2 D_p^5} \quad [9-6]$$

$$\eta_P = \frac{C_T J}{C_P} \quad [9-7]$$

Where V is the true airspeed, n represents the propeller revolutions per second, D_p is the propeller diameter, T_P is the thrust of the propeller, ρ is the air density and P_P is the power of the propeller.

As it will be commented further below, typical works on aircraft performance estimation at the conceptual level tend to employ simplifying hypotheses regarding propeller performance. For example, in classic manned aircraft design and performance references, it is usually considered that η_P has a constant fixed value through the flight (8; 405; 406). In certain cases, variations attending to the type of flight segment (climb, loiter, high speed cruise, etc.) are accounted for by proposing different typical values of η_P for these aircraft types, with this value remaining constant along the flight segment (8). This hypothesis of constant η_P is also employed in many previous references on RPA conceptual design, with most of them using values that were tabulated for manned aircraft (6; 13; 35; 115).

When the aircraft is equipped with a variable pitch propeller, the propeller performance curves can be varied by changing the propeller pitch angle, thus allowing for an additional degree of freedom. Thus, the pitch can be adjusted so that a value of η_P close to the maximum can be achieved in many different flight conditions. This supports the use of the constant η_P hypothesis in these aeroplanes, as through the pitch adjustment, this variable can be maintained at approximately the same value, and even close to the maximum, through different points during the flight. However, for fixed pitch propellers, only a single curve of η_P is available, so if there are relevant variations of J along the flight or through the mission envelope overall, the classic hypothesis might not hold.

While the use of variable pitch propellers is commonplace in manned aviation, this is not the case in RPA. This was seen in Figure 7-12, obtained from the results of the database compiled as part of this research, where for most of the RPA for which this information was found, the fixed pitch type is the one of choice. This is in contrast to the extended use of the constant η_P hypothesis for RPA in many previous works, which has already been questioned in previous research (35). Furthermore, in the case of the research conducted in this chapter, significant variations in mission parameters shall be considered, since the emphasis is on studying the multi-mission performance and multi-role design of these aircraft. When considering the aforementioned aspects, here it is sought to model the changes in C_T , C_P , and η_P as a function of J , so as to provide a more accurate estimation of the possible impact that changes in propeller performance can have in the integral performance the overall aircraft.

Since the focus of this thesis is on conceptual design, rapid methods are required, so the CFD options would fall out of the scope considered here. In the case of blade-modelled methods, the momentum theory has significant deviations from the true propeller performance in many flight conditions, and the magnitude of these errors as seen in previous works (430) could result in exceeding the acceptable error margin in conceptual design. In the case of blade element theory and related methods, they require additional knowledge of the geometric definition of the propeller, which is often not even available

in the open literature for commercial off-the-shelf ones. The empirical approaches would be the ones remaining, which are the ones to be employed in this thesis. This approach matches the scope and purpose of this research, since it is focused on the airframe design, and not on the development of the propeller itself. Furthermore, this kind of approach has already been recommended in reference (9) for general aviation aircraft design. With this, the designer would select an existing propeller whose characteristics are known, and by employing a parametric approximation of its curves, a satisfactory approximation of the propeller performance for this design stage can be achieved. Semi-empirical curves for propellers for RPA have been found in (431; 432; 433; 434; 435).

9.2.4. Flight laws, integral performance equations and PL-R/PL-E diagrams

The PL-R Diagram is a means of representing an aircraft's operational envelope which is commonplace in the field of aircraft design (7; 8; 11; 51). It is generally used to illustrate the set of missions that the aircraft can accomplish, bounded by limitations which are usually related to the Maximum Payload (MPL), MTOM and MFM. Each point within the diagram represents a particular mission, which can be calculated employing integral performance equations. Some of these points of the diagram correspond to typical operating missions, which may at times differ from the design mission which was the one employed to perform the initial sizing of the aircraft (412; 415; 416). This design mission is usually located close to the limit of the envelope (8; 412; 415). The basis on the typical use of PL-R Diagrams within the context of aircraft design is more thoroughly expounded in references (7; 51). A notional PL-R diagram is represented in Figure 9-4.

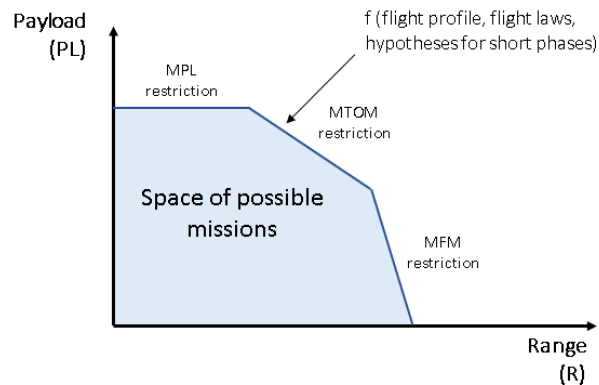


Figure 9-4: notional Payload-Range (PL-R) diagram, with the design mass corresponding to each restriction indicated.

In those cases where the endurance is a more relevant performance parameter than the range, which for example may be the case in surveillance missions, the first variable is used in lieu of the latter (25; 420). This requires to use different integral performance equations to obtain the diagram, and the result is a Payload-Endurance (PL-E) diagram. It should be noted, as indicated in Figure 9-4, that the shape and the position of the constraints in the payload-range diagram depend on various factors related to the flight

profile and flight law, amongst others. The influence of these aspects on the diagram will be a central topic in relation to the novel performance model developed in this thesis. The equations that govern the diagram and the constraints of the envelope also change depending on the type of engine, where for instance in the case of electric motors the MFM restriction is not applicable. Some references that constitute example applications of PL-R or PL-E diagrams to electric motors and hybrid engines can be found in (106; 107; 108).

In order to obtain a PL-R or PL-E diagram for an aircraft, its mission profile must firstly be defined, as the solution to the integral performance equations depends on the flight laws employed therein. Here, some of the typical simplified solutions for integral performance estimation used in the aircraft design literature shall be briefly commented. Aside from an initial classic example applicable for turbine engines, the focus shall be on equations pertaining to reciprocating engines, since they are the ones to be studied in this chapter as mentioned in 9.1.1. However, it is noted that alternative integral performance formulations for electric and hybrid powerplants have also been developed, as it can be respectively seen in the investigations of (436) and (437).

One of the most common solutions to the previous equations is presented in the form of the classic Bréguet's range equation, which is a modelisation widely employed in conceptual design studies (7; 8; 9; 11). Its form shown in equation [9-8]:

$$R = \frac{V}{C_{jm} g} \frac{C_L}{C_D} \ln \frac{W_i}{W_f} = K \ln \frac{W_i}{W_f} \quad [9-8]$$

Where R represents the range, V the true airspeed, C_L/C_D the cruise aerodynamic efficiency, C_{jm} the specific fuel consumption as defined per fuel mass flow and per unit thrust, g the acceleration of gravity, W_i and W_f are the initial and final weights of the flight segment, and K is the range factor (438). This equation corresponds to an exact solution for an aircraft equipped with a turbofan or turbojet engine when following a flight law of constant speed and C_L , and variable altitude, whereas it may be used as an approximate solution for other cases.

The equivalent solution for the case of propeller-driven aircraft is given in equation [9-9]:

$$R = \frac{\eta_p}{C_{pm} g} \frac{C_L}{C_D} \ln \frac{W_i}{W_f} \quad [9-9]$$

Where C_{pm} is the specific fuel consumption as defined per fuel mass flow and per unit power, and the rest of variables as defined before.

The Bréguet equation may also be used as an approximate solution to other scenarios, such as when considering a constant speed and altitude flight law. In these situations, the range factor is assumed to be constant during the cruise flight (438), and it is usually obtained by assuming that the relevant variables needed to determine it take values corresponding to the half-point of cruise.

In the case that exact solutions for distinct flight laws are sought, it would be necessary to consider the variations along the flight of V or C_L , depending on the flight law which is chosen. This is undertaken in the following simplified analytical equations, which shall be derived for a propeller aeroplane, and under the hypotheses of constant propeller efficiency and constant power specific fuel consumption. A transmission efficiency, η_t , will also be included to account for mechanical losses in the transmission between the engine and the propeller. Under these conditions, an exact solution can be found for range and endurance pertaining to the flight laws of constant speed and altitude, and of constant angle of attack and altitude. The following results are partly based on the development of (9). They will be formulated in terms of mass instead of weight as the former shall be the variable to be employed in the models developed within this chapter.

In the case of **constant angle of attack**, which corresponds to a constant C_L , the equations are the following:

$$R = \frac{\eta_p \eta_t C_L / C_D}{C_{pm} g} \ln \frac{m_i}{m_f} \quad [9-10]$$

$$E = \frac{\eta_p \eta_t \sqrt{2 \rho S_w} C_L^{\frac{3}{2}}}{C_{pm} g^{\frac{3}{2}}} \left[\frac{1}{\sqrt{m_f}} - \frac{1}{\sqrt{m_i}} \right] \quad [9-11]$$

This flight law has certain drawbacks, such as the need to change the airspeed along the cruise segment to maintain the same altitude as the fuel is depleted, with the added difficulties that this might imply for ATM. In spite of this, it has received a considerable amount of attention in previous works particularly within the fields of general aviation and unmanned aircraft design (6; 9; 17; 151). This may be attributed to the fact that it allows the aircraft to fly at a specific C_L of interest during the segment. This can be, for instance, the C_L of maximum endurance, thus allowing the aircraft to fly closer to this optimum condition for a longer period of time, resulting in a potentially higher fuel efficiency when compared to a other flight laws.

In the case of **constant airspeed**, an additional hypothesis is required to arrive at the following close-form solutions, with it being that the drag polar has been assumed to be of the pure-parabolic kind, that is, according to equation [9-3]. The results are:

$$R = \frac{\eta_t \eta_p}{C_{pm} g \sqrt{C_{D0} C_{D2}}} \left[\operatorname{atan} \left(\frac{m_i}{\sqrt{\frac{C_{D0} \rho S_w V^2}{C_{D2}}}} \right) - \operatorname{atan} \left(\frac{m_f}{\sqrt{\frac{C_{D0} \rho S_w V^2}{C_{D2}}}} \right) \right] \quad [9-12]$$

$$E = \frac{\eta_t \eta_p}{V C_{pm} g \sqrt{C_{D0} C_{D2}}} \left[\operatorname{atan} \left(\frac{m_i}{\sqrt{\frac{C_{D0} \rho S_w V^2}{C_{D2}}}} \right) - \operatorname{atan} \left(\frac{m_f}{\sqrt{\frac{C_{D0} \rho S_w V^2}{C_{D2}}}} \right) \right] \quad [9-13]$$

These previous equations have been formulated in terms of the initial and final mass of the cruise flight segment. As mentioned at the start of the current section, this is a typical approach of references within the area of flight mechanics. However, within the realm of aircraft design, it is required to take an additional step, which would be to relate the m_i and m_f variables to overall mass variables of the aeroplane associated with its operation, such as Landing Mass (LM), Fuel Mass (FM), Take-off Mass (TOM), OEM, and PL. This is because these variables are more tightly connected to both operational and design aspects of the aeroplane. Furthermore, they are required to plot the PL-R and PL-E diagrams, including their boundaries, which are associated to design limitations related to the aforementioned masses, such as the MPL, MFM, and MTOM.

The relationship between m_i and m_f with the aforementioned general mass variables of the aeroplane shall depend on many aspects, including the flight profile itself as well as various hypotheses with respect to the fuel-unintensive phases. In conceptual design of air transport aircraft with a single fuel-intensive segment, the norm is to consider typical values of the weight fractions of other stages such as warm up, take-off, and climb, using them to arrive to the TOM and LM, which can then be expressed as the sum of other mass variables such as the PL and FM. This process is detailed in the following classic aircraft design references (7; 8; 11; 51; 251). Once the integral performance equations are related to these mass variables, a typical procedure which is often used in the state-of-the-art to arrive at the PL-R and/or PL-E diagrams consists in defining a matrix of PL and TF values taking into account the relevant mass limitations. This set of points is then introduced in the corresponding equations, so as to map the pairs of value in the PL-TF space to points in the PL-R and PL-E diagrams (51; 408; 413; 439; 440).

In some cases where other hypotheses are considered such as the use of a three-term drag polar, when accounting for variations in the propeller efficiency, or even when considering more complex flight profiles, it might not be possible to reach closed-form equations such as those shown beforehand. In these scenarios, quasi-stationary methods may be used, which are based on a numerical integration schema that solves the horizontal and vertical force equilibrium at different steps along the flight phase, obtaining the values of the different variables and the weight variation at each point. This type of approach is seen in both analysis and synthesis approaches within the fields of manned (260; 410) and unmanned aircraft (106; 107; 108), as well as in computerised design environments such as FLOPS (86) and SUAVE (93).

With all of the above, it can be seen that the process of obtaining the PL-R and PL-E diagram does not only heavily depend on the type of flight law which is selected, but also on numerous hypothesis such as the type of drag polar or the mission flight profile. Therefore, it is seen that this subject area is tightly connected to the models selected with respect to the topics covered beforehand through this section. Taking this into account, and aside from any possible gaps pertaining to the field of RPA which may be found in relation to the the concepts commented here, any other potential areas of improvement

in terms of RPA modelling discussed beforehand will also have an effect at this point. For instance, as mentioned in previous subsections, there are few works in RPA design which have used a three-term drag polar. As commented here, the drag polar model has a direct effect on the equations used to obtain the integral performance and the PL-R and/or PL-E diagrams. Therefore, up until now, the possible effects that the consideration of this more accurate drag polar model can have in arriving to a mathematical solution which allows to obtain these diagrams, as well as the potential impact of each of the three terms in the envelopes themselves, would have yet not been analysed in detail.

Aside from these couplings with the previous topics, some specific aspects that are more tightly related to the notions commented in this subsection have also been observed in the state-of-the-art of RPA performance and design methods. As commented beforehand, the PL-R and PL-E diagrams are a useful representation of the envelope of operations that can be carried out by the aircraft, showcasing the extent of its multi-mission and off-design capabilities. In contrast, and in spite of the marked diversity of potential operations of RPA and the emphasis on their multi-mission capability, the use of these diagrams is seldom seen in previous RPA-related research. Albeit they have been employed in the works of (106; 107; 108), these investigations are focused on hybrid electric powerplants, leaving the room open to leverage the PL-R and PL-E diagrams for the representation of the mission envelope of other types of RPA, such as those equipped with reciprocating engines. A possible reason for this might be that most previous research on RPA integral-performance based design is of the AADM type, and within the development process of their specific RPA platform in each case, they are mostly focused on the design mission used to size their vehicles, without placing as much emphasis on other possible off-design capabilities.

In the case of this thesis, since the emphasis is on multi-mission RPA, these diagrams shall be essential to illustrate the ways in which the performance of the aircraft is modified depending on the different operations that can be flown through its mission space. This will include a comparison between the resulting envelope when using two different flight laws, which produces notably distinct diagrams. Additionally, as it can be seen in the equations above, the aircraft's integral performance does not only vary with the values of PL and FM (which are included in the m_i and m_f variables) but it also changes with the selected value of the variable which remains constant for each flight law, namely V or CL . This behaviour has already been observed in manned aircraft design (7; 404), with some investigations analysing the variations in the PL-R and PL-E diagrams when modifying the cruise speed, however up until now it has not been studied in detail within the realm of RPA. Furthermore, due to the focus of this research on design aspects, the sensitivity of the diagram attending to changes in key features of both the RPA itself and on other mission-related parameters will also be studied, which would constitute original analyses with respect to previous works in the state-of-the-art.

9.2.5. Overview of previous research on RPA performance estimation methods

Albeit some of the particular characteristics and gaps of previous works in the field of RPA design and performance analysis have been highlighted along the previous subsections when covering each of the individual topics, this shall be complemented with a broader overview of the general distinctive aspects of previous investigations in this area. The focus of this subsection shall be on the overall features of selected state-of-the-art research works with respect to the performance analysis models themselves, including those which are used in design frameworks. The particular ways in which these analysis approaches are then used within sizing and design workflows shall be emphasised in the following subsection.

Most of the performance analysis models usually employed within conceptual and preliminary design references of RPA tend to use the Bréguet equation shown in [9-8]. This model is often employed for flight laws such as that of constant speed and altitude, as seen in the works of (13; 25; 117; 122; 141; 142). It is noted that works in this area tend to consider, as mentioned in 9.2.1, a mission profile with ingress and egress segments. The usual approach to solve the complete operation involves using the Bréguet equation for the three fuel-intensive parts of the flight so as to estimate their weight fractions, which is complemented with the application of typical values for the fuel-unintensive ones. These considerations follow the general trend in manned aircraft conceptual design approaches (58; 415; 416). Other works have studied the constant angle of attack and altitude flight law, as seen in (6; 17; 115). However, the analysis of both flight laws along with their comparison, for instance to evaluate the ways in which they impact the mission capabilities of a specific RPA, has not been found in the state-of-the-art analysis conducted in this chapter on previous works within this topical area.

Furthermore, albeit the study within a same work of flight profiles that can model alternative missions to the typical ISR ones has been emphasised as a future line of work in the research of (6), and in spite of the mission diversity of RPA, up until now flexible approaches covering the modelisation of various mission types are seldom found in the area of RPA integral performance analysis and design. This can be attributed to the fact that many of the investigations here are of the AADM type as seen in Table 2-2, so a flexible mission profile which can cover many distinct types of operations is not required, as the focus is on the specific mission of the RPA that is being designed in each of these works, with this flight profile definition even having preset values attending to the initial requirements. A research effort which stands out with respect to mission flexibility is the one of (17), where the proposed design environment for RPA is shown to be compatible with a high degree of adaptability of the flight mission, as the operation can be built through the combination of distinct types of segments (climb, loiter, cruise, etc.). In spite of this very high level of flexibility in the mission profile definition, which is similar to that which is permitted by manned aeroplane design environments such as FLOPS (86) and RDS (99), the flight law in all cases for this RPA design environment appears to be the one

defined by a constant C_L . However, the value of lift coefficient for each segment can be set separately, thus also allowing in this regard a degree of flexibility (17).

It is noted that albeit the most common powerplant option for RPA is the reciprocating engine, which is also attending to the scope of the present chapter, other alternative integral performance models have been used in RPA performance analysis and design when employing distinct powerplants. This can be seen in the works of (115; 118; 124), which include integral performance formulations for electric motors, within the research of (106; 107; 108) which are focused on hybrid-electric powertrains, and even models for solar RPA have been developed in the investigations of (121; 130).

Now, other works shall be commented different from those above, focusing on research which addressed the performance analysis of RPA outside the scope of design approaches. For instance, in (441), which is an analysis study on a pre-defined RPA, the equations of flight mechanics are solved following time-steps along the flight, falling within the quasi-stationary approach mentioned beforehand in 9.2.4. This is one of the few works found in the state-of-the-art analysis conducted here that considers variations in propeller performance along the duration of each flight phase. This quasi-stationary technique also allows to estimate the behaviour along the operation of different variables which cannot be derived when employing approximations such as that of constant η_P . These include the propeller advance ratio, its efficiency, or the engine rotational speed, Ω_E , amongst others. The research conducted in the works of (106; 107; 108; 109) should also be highlighted. In these cases, the focus is on powerplant redesign while maintaining the airframe of the RPA fixed. This type of approach would fall outside the scope of this thesis, as it is focused on the design of the airframe itself. However, it should be remarked that, in a similar vein to the previously mentioned work of (441), they also use more accurate performance estimation models, employing a time-step calculation of the aircraft performance at each point in the trajectory and modelling the variations in propeller efficiency through the use of empirical curves, as it will be done within the models developed in this chapter. However, since they are focused on a specific aircraft, the geometry of the flight profile is fixed, so the effect of potential variations in this regard are not taken into account.

A final group of works would be those that use simulation approaches, which was one of the topical areas described and analysed in section 2.2, falling within the area of preliminary design. These have a higher level of fidelity, but they also require a more detailed definition of the aircraft to perform their calculations. These approaches do not only model range and endurance, but also other aspects that can be obtained from accurate mission simulation, such as sensor range and the probability of detection of certain targets (19; 114; 135; 136; 137; 138). This follows a parallel trend to the field of manned aeroplanes, where works performing accurate aircraft trajectory and performance simulation have also achieved remarkable results (442; 443). However, these type of approaches are only feasible for late stages in the design continuum or even

for application to an already manufactured aircraft whose aerodynamic and mass characteristics are accurately known.

Overall, it can be seen that the models employed for integral performance estimation show remarkable variations along investigations with differing scopes. The most involved performance models are usually found in works purely focused on analysis, such as the ones of (106; 107; 108; 109; 441), where the emphasis is not on design, as they study RPA with fixed geometries. However, the advantages provided by these models are remarkable, not only due to their increased accuracy, but also since they enable to study the variations along the flight of certain variables such as propeller efficiency and engine rotational speed, which would not be possible with simplified formulations. On the area of design, and even including works within the preliminary stage, most of them tend to use the Bréguet equation, two-term drag polars, a constant η_P hypothesis, and flight profiles with a fixed geometry, also fitting the fact that most methods are of the AADM type. One of the foremost aspects which could enhance the capabilities of these approaches, particularly when considering the specific features of RPA, would be the consideration of a greater mission flexibility. This aspect was already commented when analysing the design environments for RPA in chapter 4, where it was seen that most mission variations were similar to those that were taken into account in manned aeroplane design, which is in contrast to the higher degree of operation variability shown by RPA. This could allow to study the behaviour of the aircraft along a much more expansive mission space, providing more information on its off-design capabilities, and also enabling the development of multi-role approaches which consider a wide array of missions in the sizing process.

9.2.6. Outline of previous research on mission-based aircraft design

As brought forward in advance in subsection 2.1.1, the same model can be employed from an analysis or synthesis perspective. In the case of the topical area of integral performance-based sizing, the models which have been expounded beforehand in this section are typically used to estimate weight fractions of the aircraft, which then allows to reach an initial definition of its main design mass variables such as the MTOM and the MFM. Thereby, the perspective is to use the initial specifications in terms of range and endurance, along with a set of typical values, to perform an estimation of the mass that the aircraft must have to accomplish this objective operation. Enabling this mass estimation process is one of the main reasons substantiating the need of formulating the integral performance equations in terms of overall design and operational mass variables, as commented in 9.2.4. This kind of approach is commonplace in manned aeroplane design as it can be seen in classic references such as those of (7; 9; 11; 14). The aforementioned approach of using the integral performance equations to estimate mass fractions, so as to then use them to perform an initial definition of key design mass variables of the aircraft, has also been followed in the realm of RPA integral performance-based sizing (6; 25; 117; 122).

It must be noted that the hypotheses used to derive the integral performance equations have a direct influence in the capabilities and accuracy of the sizing methodologies based on those expressions. In this way, if only few degrees of freedom and avenues of variability are allowed in the performance models, when they are rearranged to perform the mass estimation, these limitations shall also apply. For instance, if the performance model has been derived only considering the constant C_L flight law, then it will not be able to size a RPA whose initial specifications include a mission with constant V . As another case, if the only type of mission profile included in the model is of type A as illustrated in Figure 9-3, then it will not be able to size the aircraft for a mission which has ingress and egress segments. Thereby, the characteristics of the performance model have a decisive influence on the sizing problems which can be solved through its use when following a synthesis approach.

Considering the above, and taking into account the comments given in the previous subsection, previous works usually only consider a single flight profile geometry, and possible variations on flight law are typically not taken into account. For the case of ADDM-type works, this is not a relevant issue, as their purpose is to design a specific RPA for a pre-defined purpose. However, in the case of research of the GDM type, this would limit their flexibility and applicability, particularly when considering multi-role RPA, as the degrees of freedom in the initial specifications of the multiple envisioned missions are limited by the capabilities of the analysis model. In any case, as already discussed both in chapter 2 and 4, currently no previous works which allow to conduct the sizing of an RPA attending to multi-role aspects in the conceptual design stage have been found in the literature.

With respect to the preliminary design phase, in this case the aircraft has already been sized beforehand, so the purpose of considering mission aspects here would mostly be to refine and optimise the initial concept. Some optimisation frameworks, as mentioned in the previous subsection, employ rapid calculation models such as those used in the conceptual works mentioned beforehand, as seen in (61; 115; 141; 142). This allows to estimate figures of merit related to the mission accomplishment and efficiency, which are fed back to the optimisation loop in the resizing process. Then, as also introduced beforehand, there are simulation-based approaches, which are usually embedded in optimisation frameworks. In these cases, higher fidelity results from the simulation are employed to resize the aircraft. Some of these works, such as those of (136; 114; 139), consider conflicting optimisation objectives of diverse operation types. Thereby, they can be considered to perform a refinement of the pre-defined RPA geometries attending to multi-mission aspects. However, the process through which the initial geometry is achieved is usually not covered in this type of works, thus leaving a gap in the conceptual design stage, where multi-role considerations could already have been taken into account so as to generate an initial concept that complies with the envisioned multi-role specifications. Then, this first definition of the RPA can be fed into the existing simulation

approaches to further refine it, leveraging the available models and optimisation frameworks currently available in the state-of-the-art.

As a comparison with the realm of manned aeroplanes, multi-role initial sizing is also comparatively scarce in this area, albeit it has seen a larger development than in RPA design. Most of these works are also focused on optimisation approaches considering conflicting objectives of distinct missions within the space of possible operations. For instance, the research presented in (408; 413) establishes a framework for transport aeroplane optimisation when considering its performance in various points of the PL-R diagram, which correspond to missions with an envisioned high degree of utilisation in the operating life of the aircraft. Then, the work of (82) analyses a military operational scenario, establishing various conflicting measures of effectiveness for the mission achievement, so as to conduct an optimisation of the overall system to maximise these features. Finally, the investigation of (409) stands out, since it has a similar perspective to the one used in the earlier design stages. In this case, the focus is on a multi-role tanker aircraft design. The research also includes an evaluation of the different resulting PL-R diagrams, thus paying attention to both off-design and multi-role aspects.

Other types of investigations that analyse in the realm of manned aircraft the connections between the mission space and design aspects are also mentioned here. The works of (412; 415; 416) stand out due to their analysis of the way in which the PL-R diagram of existing transport aeroplanes presents a certain mismatch with their most usual operations during their service life. This results from the fact that the design mission is usually selected to cover many more foreseeable routes than the ones which will then see a larger utilisation, which fall well inside the PL-R diagram. This added mission flexibility comes at the cost of a reduced operational effectiveness for the operations located inside the diagram. Thus, these studies analyse the possibility of performing an aircraft design with a reduced range which presents a higher fitness with the actual utilisation, resulting in an increment in mission efficiency. Then, with respect to mass estimation, there are other approaches aside from the ones based on the performance equations as mentioned beforehand. For instance, the investigations of (439; 440) conduct an estimation of the required FM for turbopropeller aircraft based on regressions extracted from the flight manuals of existing aircraft. These kind of approaches have not yet seen an equivalent research in the field of RPA.

All in all, and with respect to the main gaps seen in integral performance-based design of RPA, the main highlight would be the current lack of conceptual models for the initial sizing of these aircraft attending to multi-role requirements. The development of novel methodologies in this area could constitute a remarkable asset, complementing the existing simulation-based methods, which have a much higher computational cost and start from a pre-defined configuration. Aside from this, most other potential avenues of future work would be related to improvements in the performance models themselves, which have already been discussed in the previous subsection.

9.2.7. Summary of gaps towards RPA mission analysis and synthesis methods

A summary is provided here of the main gaps in the area of RPA integral performance-based design, which were already discussed through the preceding subsections. These areas of potential improvement shall be related with the main characteristics and challenges of RPA, and they shall guide the development of both the analysis and synthesis approaches to be developed in this chapter.

It can be seen that there is room for improvement for both analysis and synthesis approaches for RPA. In particular, with respect to the conceptual design works analysed above, the following gaps have been detected:

- 1) **Need of a higher mission flexibility:** most previous works are focused on a specific mission type, thus employing a single flight profile, which in most cases is described by a fixed set of values. Furthermore, usually a single type of flight law is considered. This is according to the needs of AADM approaches. However, when considering the mission diversity of RPAS, a GDM methodology would greatly benefit from being able to model a higher variety of operations (ISR, SAR, cargo transportation, etc.), as this would expand its applicability range. This added mission flexibility would allow to analyse a wider array of off-design missions from an analysis perspective, and it would also permit to conduct the sizing of multi-role aircraft with specifications pertaining to remarkably distinct operations when used from a synthesis viewpoint. This area of future work was already highlighted in the research of (17; 70).
- 2) **Current lack of initial sizing multi-role methods:** In spite of the recognised multi-mission nature of many RPA and the fact that this can be considered one of the main current challenges for the design of aircraft as laid out in section 1.3, no conceptual design approaches for the initial sizing of multi-role RPA have been found in the state-of-the-art analysis. The introduction of these capabilities in design approaches would constitute a noteworthy asset, as it could allow to tackle one of the main challenges of RPA design as laid out in section 1.3, which is that of multi-role design.
- 3) **Improvements in model adequacy to RPA characteristics:** as seen beforehand, most works on RPA integral performance analysis and design use two-term drag polars and assume a constant propeller efficiency. Albeit these hypotheses are well-suited for the characteristics of typical manned aeroplanes, the high camber profiles used in many RPA wings, as well as the ubiquity of fixed-pitch propeller might require to consider the use of other models to ensure with a higher degree of confidence the validity of their results. However, up until now, very few works have used a three-term polar for RPA performance analysis and design, and none in the conceptual design area have considered variations in η_p . This last aspect

has, however, been taken into account in certain performance studies (106; 107; 108; 109; 441).

- 4) **Study of changes of relevant performance variables along the flight:** if the above-mentioned hypotheses of three-term drag polar and variable η_P are to be considered, the solution of the integral performance equations will require the use of quasi-stationary numerical approaches. In any case, one of the main one of the main advantages of these techniques when used alongside the more involved models mentioned above, is that they allow to obtain the variation history of various parameters along the flight, including the propeller efficiency or the engine revolutions (441). This can not only provide valuable information, but also allow to check whether additional operating limitations are verified.
- 5) **Consideration of various possible aircraft configurations in the sizing process:** this links with another one of the main current challenges of RPA design as laid out in 1.3 and also highlighted by previous research (21). Currently, most integral performance based approaches only perform the design attending to one possible configuration, so the possibility of comparing the performance of various layout alternatives for a single set of mission requirements would constitute a significant aid for the designer to select the most promising candidates moving forward. Even in current multi-mission optimisation approaches, as the RPA geometry is pre-defined, usually only one configuration is considered.

9.3. Development of novel RPA performance and design models

As seen in the gaps analysis presented beforehand, and as it has also been highlighted by previous research (17), the remarkably distinct operational landscape of RPAS demands the development of novel design and analysis tools to aid the designer in navigating this complex paradigm, which showcases multiple dimensions of possible variations. The state-of-the-art analysis conducted along the previous section has revealed some areas that could be further improved so as to aid the designer in tackling current RPA design challenges, particularly those related to the diversity of missions that these aircraft can accomplish, as well as to allow to perform the sizing of multi-role RPA. This supports the need to develop new analysis and synthesis models to cover the current needs and gaps that have been identified, as brought forward in advance within the introduction to this chapter.

This section covers the development of the new analysis and synthesis approaches for multi-role RPA proposed among the contributions of this thesis. The main guiding principles when creating these methodologies have been both the objectives and scope laid out in 9.1.1, as well as the gaps compiled in 9.2.7. References shall be made to these

points along the current section so as to substantiate the main decisions and hypotheses considered along their development.

The first subsection, 9.3.1, covers the development of the analysis approach; and then in 9.3.2 the aforementioned paradigm shall be leveraged, along with other aspects, to elaborate a synthesis procedure for multi-role RPA.

9.3.1. Rapid performance estimation method for multi-mission RPA

The main purpose of the performance analysis model developed here is to obtain a thorough description of the mission envelope of a given RPA. This includes the identification of the boundaries of the operational space, as well as an evaluation of the behaviour of key performance variables both through the space of possible missions, as well as along the duration of the flight for each of the operations included in the envelope. Following the schemas illustrated in Figure 9-1 and Figure 9-2 and considering that this is an analysis approach, here the aircraft's geometric and design mass variables are an input of the process. Nevertheless, as this procedure is later to be used in the design process, and it pertains to the conceptual design stage, only a simplified description of the aircraft will be required to apply this methodology.

(a) Main rationale behind the performance analysis methodology

Before delving into the hypotheses and mathematical basis of this approach, its overall underlying idea is expounded here, with Figure 9-5 representing a simplified schema to support the following description.

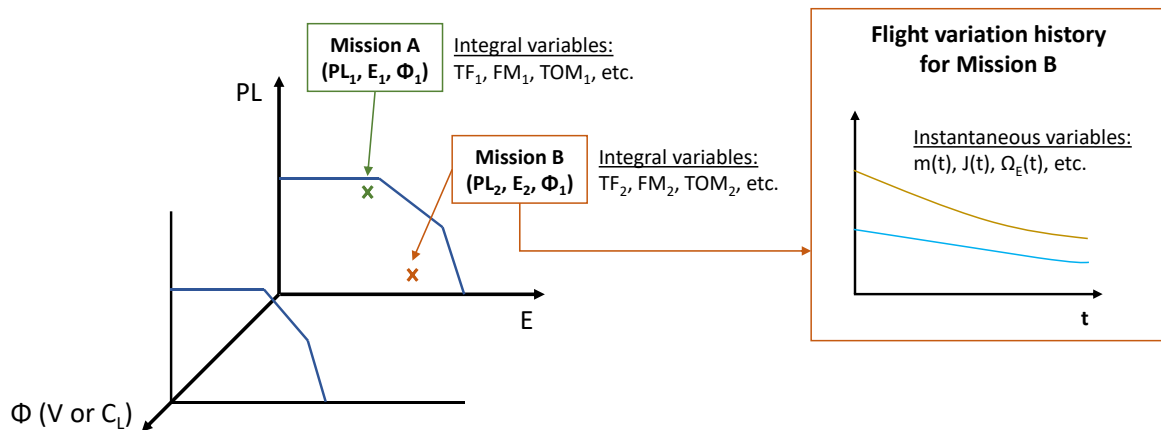


Figure 9-5. Simplified schema illustrating the main underlying idea and purposes behind the proposed performance analysis methodology. Φ represents the flight law, which in this case can either be defined by a constant speed or lift coefficient. The meanings of the remaining variables have been given previously along the text.

As mentioned in 9.2.4, the PL-R and PL-E diagrams constitute useful representations of an aircraft's mission envelope. The most usual representation found in the literature

considers a two-dimensional diagram, represented by the variables PL and either R or E . However, in the case of the constant V flight law, as seen in equations [9-12] and [9-13], the resulting range and endurance also depend on the selected value of cruise speed. A similar scenario arises in the case of a constant C_L flight law, but in this case when modifying the value of this variable, as seen in [9-10] and [9-11]. Therefore, a third dimension to the diagram could be considered, as it has been represented in Figure 9-5 for the case of a PL-E representation, with the envelope and the characteristics of its points varying along this axis. This behaviour was anticipated at the end of 9.2.4, where it was seen that up until now very few works had explored the variations in the aircraft's missions along this additional dimension, with those of (7; 404) being among those which had analysed the corresponding changes that it entails in the diagrams. With respect to the figure, it is noted that the variable Φ has been defined as a selector of flight law, which will be modelised in the mathematical formulations developed later along this subsection.

Each point in the PL-E diagram represents a different sortie of the aircraft, with each of them consisting on a series of mission segments. When comparing different points of the diagrams with one another, there are several variables that change between them. In this work, these have been called “**integral variables**”, as they represent the full flight, and thus do not change along its duration. Now, focusing on a particular point of the diagram, for instance on Mission B, this sortie can be modelled through a time (or space) variation of several variables which change along the flight. These have been named “**instantaneous variables**”. For these, it is not sufficient to select a point in the PL-E space to know their values, as it was the case for the integral variables. Rather, the instant of time along the flight needs to be given too so as to know their values. Some examples of each of these variable types are shown in the figure.

Both the values that the integral values take on each point of the PL-E continuum, as well as the variations that the instantaneous variables experiment through each of the flights contained in the PL-E diagram provide valuable information both from the operational and design standpoints. For the conceptual design stage, these results deliver a thorough description of the performance of its aircraft through many dimensions of variation of its space of feasible missions. Thus, it can be known how much FM must be loaded in the aircraft to carry a certain payload to a specified distance, or what will the Landing Mass (LM) of the aircraft be upon recovery. Furthermore, they allow to identify potential limitations to the mission space. As a matter of fact, the three main restrictions of these diagrams (MPL, MTOM, MFM) correspond to the loci of points where PL, TOM, and FM are respectively equal to their maximum values. Furthermore, knowledge about the history variation of the instantaneous variables along the flight can reveal new restricted areas of the envelope. This could be the case, for instance, if a mission exceeds at a certain point the maximum value of the engine Ω_E , which is a piece of information which would not be known if the variation history of this variable along the flight is not computed.

Previous works in the manned aeroplane field have leveraged the analysis of integral variables along the PL-R diagram's continuum to a remarkable effect. For instance, in the line of research developed in references (412; 415; 416) about the mismatch between the design point and the utilisation of airliners, the variation of TF in the points inside the diagram was studied as a previous step to then propose the approach of designing an aircraft according to its utilisation, thus changing its PL-R envelope. The research developed in (404) also studied the ways in which the design point of the aircraft affected its efficiency through the rest of the missions of the PL-R diagram. It is noted that this work also considered the way in which variations in flight speed affected both the limitations of the envelope as well as the integral variables of the interior points of the diagram. Furthermore, the investigations of (408; 413) also study the evolution of various characteristics, such as the TF, along the diagram, so as to use the values of these features along the mission space to perform an optimisation of the aircraft considering its full envelope. However, from the findings of the state-of-the-art overview conducted in 9.2, this kind of comprehensive analysis of the mission space has not been found beforehand in the field of RPA performance and design. Furthermore, the study of the variations in the instantaneous variables through the mission space has not been seen in previous works within the context of manned and unmanned conceptual design, thus constituting a novel approach in this research.

Albeit there is a substantial volume of information to manage when considering the results of analysing the integral variables along the multi-dimensional space represented in Figure 9-5, there are ways to present this data in a relatively compact manner while prioritising the aspects that are of the most interest of the designer. Thus, the concept of the iso-curves and their relationship with the diagram limitations are introduced here. In Figure 9-4, a notional PL-R diagram with its main limitations (*MPL*, *MTOM* and *MFM*) was shown. However, it should be noted that those specific curves for each limitation are really part of an ensemble of iso-curves representing the distinct values that the associated mass can take. This is better viewed in Figure 9-6.

It can be seen that there are a set of curves for different values of *TOM* and *FM*, with the associated value growing as the distance to the axes increases. The position and shape of this curves is a function of different variables involved in the integral performance calculation, such as the drag polar coefficients. For instance, when comparing two aircraft, one with a lower value of *C_{Do}* and another with a higher value, and considering that both share the same *TOM* for a certain operation, the first one will be able to travel farther than the second, thus having distinct ranges. The iso-curves whose value coincides with the design mass limitation of the aircraft, which will be approximately parallel to the rest in the same family of iso-curves, sets the limits of the PL-R diagram, as seen in Figure 9-6, coinciding with the concept of the relation between the integral variables and the envelope limitations which was commented beforehand. A more thorough exposition of the calculation of the iso-curves and their meanings can be found in (404).

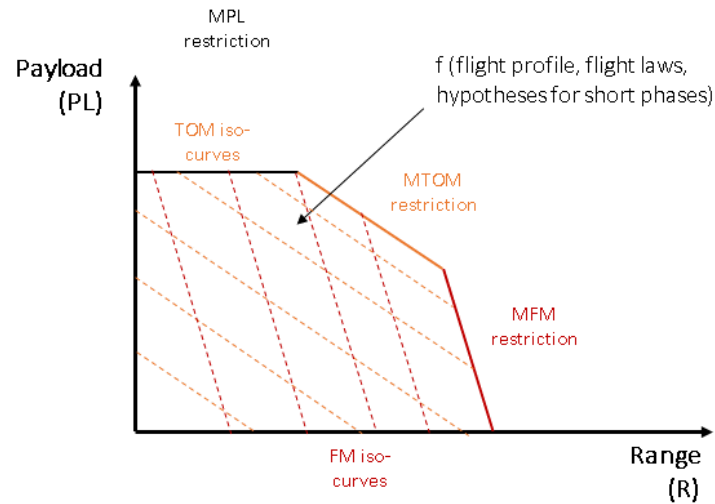


Figure 9-6: representation of TOM and FM iso-curves and their relationship with the limitations of the PL-R diagram.

Furthermore, aside from iso-curves of integral variables, the corresponding loci of points related to instantaneous ones can also be obtained. However, as these variables vary along the flight represented by each point, it is necessary to establish an additional criterion with respect to the value that is to be kept of their history variation. In this work, four different criteria shall be used: the maximum value along the flight, the minimum value, the average value, and the difference between the maximum and minimum values (henceforth named delta). For instance, if the instantaneous variable to be studied is Ω_E , and it is sought to study its maximum values, for each point in the diagram, only the highest value of engine revolutions along each flight is kept. Then, this is treated as an integral variable, and the iso-curves are represented.

The rationale outlined above provides an overview of the main purpose of the method to be developed here, its operating steps, and the outputs which it seeks to obtain. However, there are more aspects that will be considered aside from the ones discussed here. For instance, the shape of the PL-R and PL-E diagrams does not only depend on the flight law and the particular value of its defining variable which are selected, as it is also a function of the flight profile geometry, the weight fractions of other flight phases, and the altitude, among other aspects. These shall be further developed through this subsection.

(b) General hypotheses of the methodology

In order to complement the overall scope and boundaries of the two methodologies to be developed within this chapter that were already stated in 9.1.1, here, a summary is provided of the general hypotheses which have been employed when deriving the methodology. Further considerations that are more specific in nature shall be given along the remainder of the text.

- As mentioned in 9.2.2 and attending to the typical speed range of RPA as it was seen in Figure 7-27 which was obtained from the database, compressibility effects can be neglected with minimal loss of applicability. Thus, the flight condition will always be considered within the low-subsonic regime.
- The specific fuel consumption of the engine, C_{pm} , shall be considered constant and equal to a characteristic value. While in turbine engines certain scenarios demand to consider variations in this variable, this hypothesis is much more robust in reciprocating engines, as supported by (406).
- As substantiated beforehand through 9.2, and also attending to the gaps of the current state-of-the-art, these two following aspects shall be considered, in contrast to previous works: a three-term drag polar, and a variation of the propeller efficiency with the flight conditions.
- The atmospheric model shall be that of the International Standard Atmosphere (ISA).
- Since this is an aerodynamic method, it is considered that the values pertaining to the geometry, design mass variables, and other descriptive characteristics of the aircraft are known. In this case, the configuration type is not required to be explicitly stated, as this information is already contained in the drag polar which serves as an input to the model, as well as possibly in other characteristics of the aircraft's geometry which also serve as inputs. The way in which the drag polar links with the aircraft's configuration was expounded in 4.4.6.

(c) Mission geometry definition, segments, and flight laws

With respect to the mission profile to be considered for the proposed methodology, as it has been commented before, the selected option must adequately represent the missions to be modelled within the scope of this approach, balancing mission flexibility with model complexity. Previous works that have focused on the analysis or design process of a particular RPA (those of the ADDM type) have usually defined a specific mission profile at the start which is representative of the design mission of that singular RPA (25; 107). This profile is then used through all the analysis or synthesis approach.

However, here the objective is to develop a broadly applicable design methodology which can analyse distinct missions. In this way, it is sought to provide the possibility of covering a wide range of scenarios within the mission space of the aircraft. Furthermore, with respect to the use of this analysis approach within the design methodology to be developed in 9.3.2, the initial specifications related to the mission requirements of each RPA can be different, and it is also intended to cover a wide range of design missions for multi-role RPA design. Thus, one of the main objectives of the methodology developed here is that it is applicable to a broad spectrum of RPAS operations.

Considering the multi-role capability of RPAS, and the purpose of this method to be able to model many missions so as to be broadly applicable to RPAS performance analysis, two main options are considered:

- 1) A variety of mission profiles with diverse geometries must be considered within the model, and depending on the mission type, one of them is selected.
- 2) A flexible mission profile with a parametric definition is proposed so that it has a sufficiently broad applicability, being able to represent a wide array of common RPAS missions. This profile is adapted to distinct operation types by varying its parameters.

The selected approach is the second one. This is due to a parametric mission profile being easily adjustable to different mission geometries in the analysis method, or mission specifications in the design approach. By using the same underlying model and varying the values of its defining features, parametric analyses can be conducted over the same mission. For instance, this approach simplifies the process of modifying the value of the variable corresponding to the selected flight law, as mentioned beforehand when expounding the third additional dimension of variation in Figure 9-3. From a computational standpoint, the implementation of this approach is also more straightforward, as only a single model has to be defined, and issues of matching the inputs or mission specifications to the best profile can be circumvented.

In contrast, the main drawback of this approach is that, since it is defined through a baseline geometry and variants of the operation are obtained by modifying the parameters, some mission types may not fit within the possibilities permitted by the degrees of freedom of the geometric definition. However, as it will be seen, even with this second approach and by selecting an adequate baseline profile, it is feasible to provide a satisfactory modelisation of the most common mission types of RPAS, such as ISR, aerial mapping, aerial photography, SAR, and cargo transportation missions, which are amongst the most extended applications of RPAS in the civil domain (1; 6). Therefore, it is considered that this approach can adequately balance an extended mission flexibility with a moderate implementation complexity, particularly considering that it is a method intended for use in the conceptual design stage.

Considering the above, and seeking to define a parametric flight profile which can most easily adapt to the aforementioned usual operations of RPAS, the proposed mission definition is given in Figure 9-7, and it will be expounded thoroughly below.

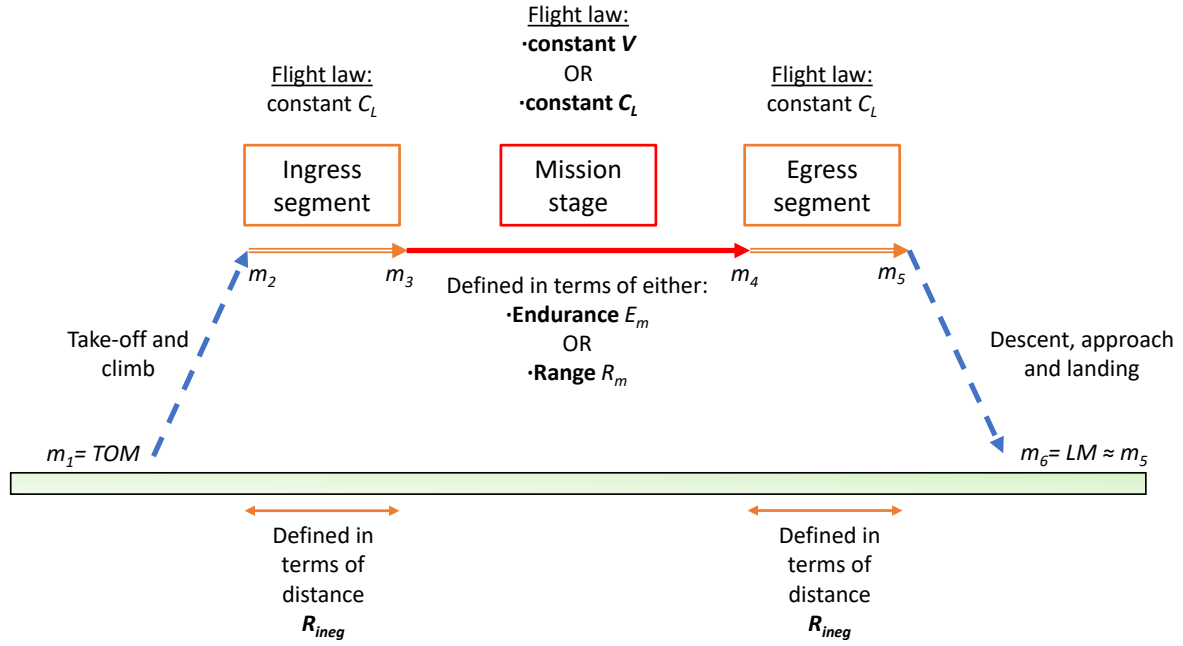


Figure 9-7. Proposed mission profile to be used in the performance analysis methodology, comprising three fuel intensive segments and allowing parametric variations. Symbols in bold indicate values which can be directly modified by the designer. The values of m_i represent the mass of the aircraft at each of the segment begin and end points. The definition of other variables is given in the main text.

It can be seen that this mission profile is comprised of two fuel-unintensive segments at the beginning and at the end of the flight, and three fuel-intensive phases. Of these three, two are positioning flights, represented through both ingress and egress segments; and the remaining one is the mission stage, with this being the part of the flight in which the purpose of the sortie itself is carried out (aerial photography, surveillance over a certain area, pipeline monitoring, cargo transportation, etc.). The main characteristics regarding the modelisation and hypotheses of each of these segments are described in detail below:

- Take-off and climb:** at the conceptual design stage, it is usual to employ simplified hypotheses to model these flight phases, as their contribution to the overall fuel consumption is low when compared to the longer stages. This is particularly true for RPA with reciprocating engines, which considering their usual missions, typically have comparatively low operating altitudes and flight speeds. Thus, as it was commented in 9.2.1, a fuel fraction value shall be employed to model these flight stages. This fuel fraction can be obtained from the following expression:

$$\frac{m_2}{TOM} = 1 - \beta \quad [9-14]$$

Where the β factor represents a typical value as obtained from the literature. Within previous works, a typical factor of $\beta = 0.05$ is recommended to model the fuel consumption in take-off and climb for a generic piston-engine RPA mission

(67). Nevertheless, the designer can also select other values depending on the singularities of the particular type of operation which is being modelled. Furthermore, the horizontal distance travelled from the take-off point to the top of climb is neglected when compared to the distance covered in the full mission.

- **Approach and landing:** previous works in the area of manned aeroplane conceptual design typically assume that the fuel consumed in these phases is modelled as that which the aircraft would spend upon continuing a level flight from the top-of-descent up to the vertical to the landing area (58). In the case of RPA, previous references have substantiated that the amount of fuel consumed in these stages can be considered negligible (67; 441), which is the hypothesis that will be used here.
- **Reserve fuel (RF):** as mentioned beforehand, in the conceptual design stage, it is usual to model the amount of reserve fuels through a weight fraction, in a similar vein to the fuel-unintensive segments. The reserve fuel fraction, α , is defined here as:

$$\alpha = \frac{RF}{LM} \quad [9-15]$$

With a typical value for RPA being a fraction of 7% (13; 67). This value can also be adjusted by the designer attending to the operation, and it should also be noted that for some RPA which have recovery means such as a parachute or similar, this value may be further reduced or even made zero.

- **Ingress-egress:** the distance covered in each of these segments is annotated by R_{ineg} , which is a value that is expected to be known by the designer depending on the kind of mission to be flown. Thus, it can be established by the designer to adapt the profile to the particular mission geometry. A possibility is setting $R_{ineg} = 0$, in which case the proposed profile will become analogous to the mission profile A that was shown in Figure 9-3. Further considerations with respect to these stages are given below:
 - In this model, the ingress and egress flights shall be considered symmetrical. This usually represents that the aircraft sorties from a certain base, and after conducting the mission, arrives back at the starting location. Thus, $R_{ingress} = R_{egress} = R_{ineg}$.
 - The flight law employed here shall be that of constant angle of attack (constant C_L). This is due to this cruise type being more adequate to optimise the specific range (9). As the mission itself is not being conducted in this stage, and the only purpose is to get the RPA to the relevant area while consuming the less amount of fuel possible, any potential restriction on the flight law that could be imposed by the

mission or payload sensor can be neglected, with the priority being to optimise range performance, thus this flight law is chosen.

- It is noted that, for a piston engine aircraft and irrespective of the drag polar model, under the hypotheses of both constant C_L and h , the propeller efficiency is constant. This solution can be reached through the application of the definition of η_P and the flight law equations. With this, and considering that the ingress-egress range is an input of the performance analysis to be conducted, and employing equation [9-10], the following expressions for the mass of the aircraft at the beginning of the mission stage and at its end can be derived:

$$m_3 = TOM(1 - \beta)e^{\frac{R_{ineg}C_{pm}g}{\eta_p\eta_t C_L/C_D}} \quad [9-16]$$

$$m_4 = \frac{OEM + PL}{(1 - \alpha)} e^{\frac{R_{ineg}C_{pm}g}{\eta_p\eta_t C_L/C_D}} \quad [9-17]$$

- The value of C_L for this flight phase is not established in the model as a degree of freedom available to the designer. Instead, and in view of the equations above, the value shall be numerically computed so as to optimise the $(C_L/C_D) \cdot \eta_P$ product, so that the highest specific range is achieved. This optimisation is conducted considering aerodynamic (stall) and propulsive (engine revolutions and propeller tip Mach) restrictions, in order to ensure a feasible flight condition.
- **Mission stage:** this is the phase of the flight in which the time or distance spent actively contributes to accomplish the purpose of the RPAS sortie. In most cases, it can be expected that it will be the segment where the payload will be active and developing its function, particularly when it is a sensor payload. This segment is resolved through a quasi-stationary approach based on time-steps, as it will be detailed later below. Some aspects related to this stage are the following:
 - The flight law used in this stage can be selected by the designer. The two options considered here, which are the most widespread seen in the RPA design literature, are the constant V and h law, and the constant C_L and h law. As mentioned beforehand in 9.2.5, no previous works were found pertaining to the conceptual design stage of RPA which considered both types of flight laws within the same model.
 - The choice on one law or the other shall mostly depend on the specific mission type, and even on the characteristics of the payload sensor with respect to accomplishing its task, which may be particularly relevant in operations such as aerial mapping. Overall, the constant V flight law is easier to manage from the viewpoint of aircraft navigation, but it can

result in suboptimal performance, as the C_L needs to change, and even if the flight is conducted at values close to the optimum C_L value in terms of range or endurance, its variation will eventually separate the aircraft from the optimum point. When using a constant C_L law, this problem is averted. Furthermore, since the attitude of the aircraft is maintained constant, this could aid certain sensor pointing requirements. On the other hand, the information gathering can be hindered due to the variable airspeed, and there are additional difficulties with respect to navigation and ATM.

- It is noted that the analysis of the variation of the different flight characteristics which is conducted with this methodology allows to monitor the variable which is distinct from the one established in the flight law. This can allow to detect possible diversions which are inadmissible from the design or operational viewpoints, such as C_L values above stall.
- The mission segment can be evaluated in terms of range or endurance, depending on the type of operation which is being conducted. The case of range covered by the flight can be more typical of missions requiring to map an area or to inspect an element such as a pipeline, whereas the endurance scenario would be more common for surveillance or reconnaissance missions. It is noted that albeit in Figure 9-7 the mission segment is represented by a straight line, depending on the case it could be the mapping of an area following a zigzag pattern (217), or a continuous loiter over a point of interest.
- The values of R_m and E_m of the mission segment are not given by the designer, since they are in this case precisely the outputs of the process, as the interest is on evaluating the mission space of an already given RPAS. In the design method to be developed in 9.3.2, the process follows the inverse workflow.

The degrees of the freedom of the model, which have been expounded above and were outlined in bold in Figure 9-7, provide a remarkable level of flexibility to the flight profile. For instance, by setting $R_{ineg} = 0$, and establishing a mission segment defined in terms of range with a constant V flight law, a classic cargo transportation mission similar to mission profile A of Figure 9-3 can be attained, with the added benefit of being able to define different flight speeds for the cruise segment to analyse the changes in the PL-R and PL-E diagrams. A surveillance mission similar to the one illustrated in mission profile B of Figure 9-3 can also be achieved by setting a certain value of R_{ineg} , and defining the mission segment in terms of endurance, with a flight law that could be either of the two. This flight profile model allows to cover most of the missions falling within the ISR, SAR,

cargo delivery, and aerial mapping or photography seen in previous RPA design works both of the GDM and AADM types.

On the other hand, certain kinds of missions – such as combat ones or those in which the trajectory is dynamically decided during flight - would fall outside the applicability scope of this mission profile. This includes certain operations which are more tailored for specific missions, such as the hurricane tracking one studied in (17). However, it is considered that through its degrees of freedom of the current model, it allows to encompass the majority of most common RPA mission types. This mission flexibility enables to address one of the main gaps commented through this chapter that even affects the field of computerised environments, as highlighted in chapter 4, where it was seen that most missions used for RPA were in reality based on those of manned aeroplanes.

As mentioned at the start of this subsection when outlining the purpose of the performance analysis approach, the final purpose is to estimate not only R_m and E_m for the mission segment, but also the change history of all other key variables in the flight. To accomplish this, it is first required to initialise the method. Since the aircraft's definition is known at the start of the process, the relevant design masses such as OEM , MPL , MFM , and $MTOM$, are among the input data of the model. As mentioned beforehand, and through a similar approach to that followed by previous works (51; 408; 413; 439; 440), a matrix of feasible combinations of values of TF and PL is generated, taking into account the restrictions related to the aforementioned design mass variables. In the case of this methodology, an additional dimension is considered, which is the set of values of the flight law variable to be considered, resulting in a 3-dimensional space. It is noted that the PL-R and PL-E diagrams to be represented shall be expressed in terms of R_m and E_m , since the performance in the mission segment is the one of most interest here.

With this set of input values, the fuel-unintensive segments and the ingress and egress ones can be solved through the process and equations laid out above. This allows to reach the values of m_3 and m_4 , which represent the mass values at the beginning and at the end of the mission segment. However, to solve this last part of the flight, and due to the complexity of the integral performance equations when considering a three-term drag polar and a variable propeller efficiency, a quasi-stationary approach is required. The process of solving this segment, which is key to obtain the change history of the key flight variables, is expounded below.

(d) Quasi-stationary numerical schema for the mission stage

With respect to the mission stage, and considering both the objectives for the methodology developed here, the mathematical nature of the problem at hand, as well as following similar quasi-stationary approaches applied by previous works, a numerical time-step approach is defined to obtain the solution of the mission segment. The resolution diagram is illustrated in Figure 9-8 and will be explained in detail below.

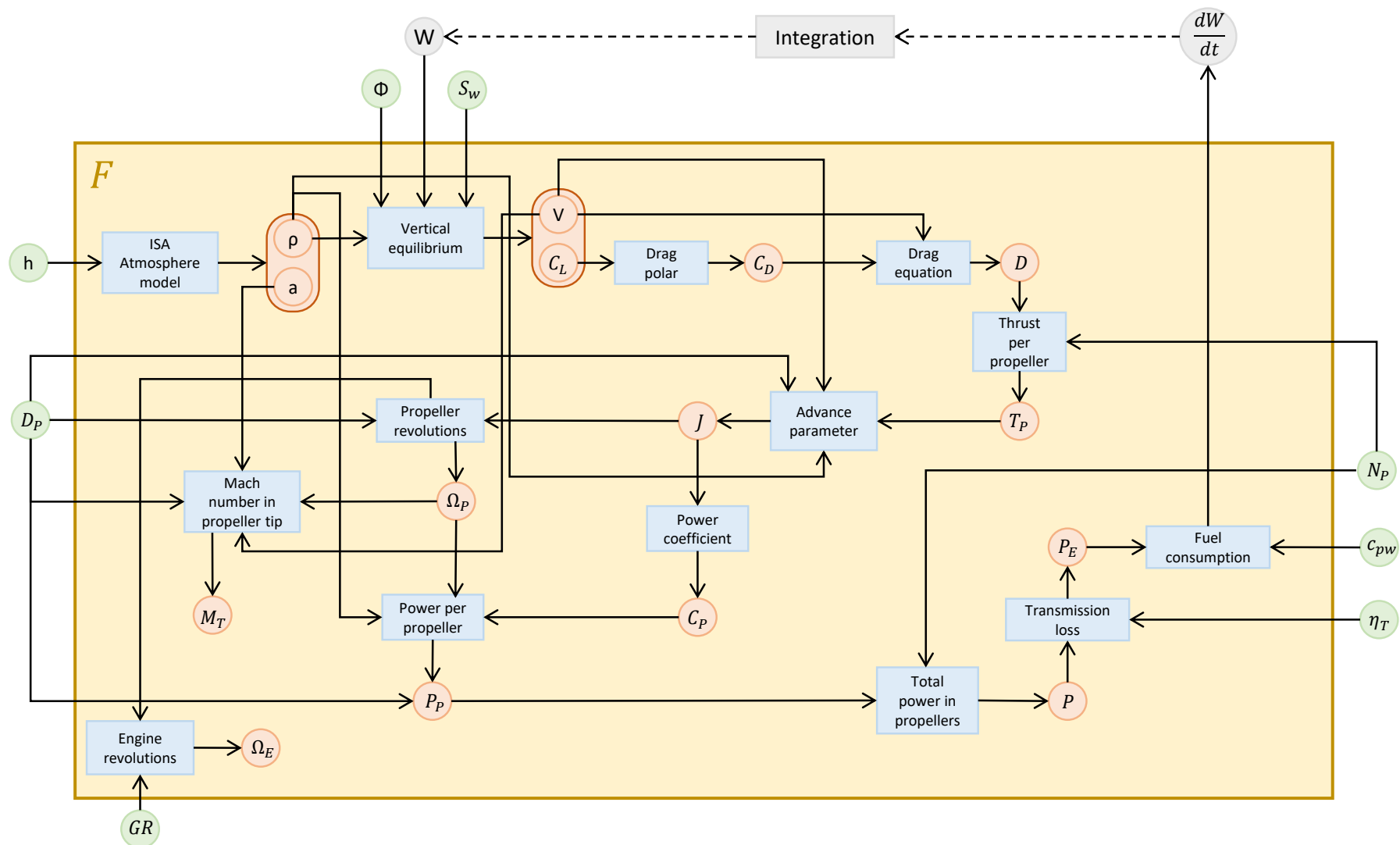


Figure 9-8. Computation diagram of the performance model for the mission stage. Symbols are defined in the main text and in Table 9-1.

The variables of the diagram along with their meanings are provided in Table 9-1.

Table 9-1: symbols and interpretation employed in the computational procedure for performance resolution at the mission stage.

Symbol	Interpretation
a	Speed of sound
C_D	Drag coefficient
c_{pw}	Specific fuel consumption per unit power and weight
C_L	Lift coefficient
D	Drag of aircraft
GR	Gear Ratio (i.e., ratio of engine angular velocity and propeller angular velocity)
h	Flight altitude
J	Advance parameter of propellers
M_T	Mach number at propeller tip
N_P	Number of propellers
P	Useful power output of all propellers
D_P	Propeller diameter
P_E	Total power at the output of the engine(s)
P_P	Useful power by each individual propeller
S_w	Wing surface
T_P	Thrust per propeller
V	Flight speed
W	Instantaneous weight of the aircraft
$\frac{dW}{dt}$	Variation in the instantaneous weight of the aircraft
η_T	Transmission performance (i.e., ratio of power at the propeller shaft and the power at the output of the engine(s))
ρ	Air density
Φ	Flight law (constant speed or constant lift coefficient). In addition to the type of flight law, it also specifies the value of the flight law variable (speed or lift coefficient).
Ω_E	Angular velocity of engine
Ω_P	Angular velocity of propeller

The diagram of Figure 9-8 depicts the computation of the time derivative of weight dW/dt (due to fuel consumption) that is required by the aircraft (characterised by its constructive parameters) to maintain a given flight condition (specified by the flight law and altitude) for a given instantaneous weight W . The set of operations that relate these two variables has been encapsulated in the block highlighted in yellow and named function F .

In addition to the model parameters (represented as green circles), function F takes the instantaneous weight of the aircraft W as its only input variable, and returns its time derivative dW/dt as an output. Furthermore, the flight law is given by the following type selector:

$$\Phi \in \{V, C_L\} \times \mathbb{R}^+ \quad [9-18]$$

Which represents that the flight condition belongs to the cartesian product of a variable selector (representing the chosen flight law, either constant airspeed and altitude, or constant angle of attack and altitude) times a value of the selected variable which is a positive real value.

Let Λ represent the set of parameters. Then function F can be mathematically expressed as:

$$\frac{dW}{dt} = F(W, \Lambda) \quad [9-19]$$

This forms a differential equation, the direct integration of which provides the time evolution of weight over time $W(t)$, which in turn would allow to compute the time evolution of any of the intermediate variables shown in Figure 9-8. These are the instantaneous variables mentioned beforehand at the onset of this subsection (represented here as orange circles).

In particular, it would be possible to compute the time evolution of velocity, whose integration with respect to time would result in the time evolution of distance flown:

$$r(t) = \int_{t_0}^t V(\sigma) d\sigma \quad [9-20]$$

However, instead of solving these two problems sequentially, it is possible to combine the two problems into a single vector integral, as will be demonstrated next:

The derivative of time with respect to weight can be derived from expression [9-12]:

$$\frac{dt}{dW} = \frac{1}{F(W, \Lambda)} \quad [9-21]$$

The derivative of distance with respect to weight can be computed by multiplying the instantaneous flight velocity with the derivative of time with respect to weight. Since, as depicted in Figure 9-8, the flight velocity is an intermediate outcome of function F , there exists a function G such that:

$$V = G(W, \Lambda) \quad [9-22]$$

And therefore:

$$\frac{dr}{dW} = V \frac{dt}{dW} = \frac{G(W, \Lambda)}{F(W, \Lambda)} \quad [9-23]$$

The values of distance flown and time in flight result from the integration of the previous expressions as follows:

$$\begin{bmatrix} t(W; \Lambda) \\ r(W; \Lambda) \end{bmatrix} = \int_{w_0}^W \begin{bmatrix} 1 \\ F(\sigma; \Lambda) \end{bmatrix} \frac{G(\sigma; \Lambda)}{F(\sigma; \Lambda)} d\sigma \quad [9-24]$$

From which endurance and range are the values when all available fuel for the mission segment (defined as the difference $m_3 - m_4$) has been consumed. The classical Simpson's rule for numerical integration is employed.

In the following, the function F and its associated operations are developed.

The first stage in the graph is the evaluation of the air density and speed of sound, both of which are calculated from the flight altitude using expressions of the ISA. It should be noted that, since altitude is constant due to the flight laws that have been considered, the computation of density and speed of sound does not depend on any variables that evolve with time and therefore could be extracted from function F for greater computational efficiency.

Since the model considers level flight, the vertical equilibrium expression states that the lift must be equal in magnitude to the weight:

$$L = \frac{1}{2} \rho V^2 C_L S = W \quad [9-25]$$

In this expression, the density, wing surface and weight of the aircraft are known, which allows to determine the value of the product $V^2 \cdot C_L$. It can be subsequently separated into the individual values of velocity and lift coefficient using the flight law (constant velocity, or constant lift coefficient).

Once the value of the lift coefficient is known, it is possible to determine the drag coefficient using the drag polar. According to the hypotheses mentioned beforehand, a three-term polar is assumed:

$$C_D(C_L) = C_{D_0} + C_{D_1} C_L + C_{D_2} C_L^2 \quad [9-26]$$

The aircraft drag force can be obtained from the drag coefficient, the air density, the speed of flight and the wing surface of the aircraft:

$$D = \frac{1}{2} \rho V^2 C_D S \quad [9-27]$$

Albeit many RPA are equipped with a single engine and propeller, the model also considers the possibility of multiple engines and propellers. It assumes that all of them contribute equally to the thrust of the aircraft. Assuming that in level flight the drag is equal in magnitude to thrust, the following equation combines the horizontal equilibrium and the distribution of thrust amongst the propellers:

$$T_P = \frac{D}{N_P} \quad [9-28]$$

As seen in subsection 9.2.3, the advance parameter is the main variable in the description of propeller performance (425) (426). It is determined by solving the following equation:

$$C_T(J) = \frac{T_P J^2}{\rho D_P^2} \quad [9-29]$$

The above equation is derived from the definition of the thrust coefficient of a propeller, introducing the definition of advance parameter to remove the dependency with the angular velocity of the propeller. Function $C_T(J)$ is an input of the model that describes the dependency of the thrust coefficient of a propeller with its advance parameter. In this work, polynomial functions are assumed.

The angular velocity of the propeller can be derived from the advance parameter, diameter of the propeller, and flight speed by direct application of the definition of the definition of the advance parameter:

$$\Omega_P = \frac{2\pi V}{J D_P} \quad [9-30]$$

The factor 2π is introduced to convert the revolutions (n) to angular velocity expressed in radians per second.

By using the Gear Ratio (GR) parameter, the engine angular velocity, Ω_E , can be computed. It is noted that this intermediate result is not employed in further steps of the model, but it serves to verify that no engine limitations related to this variable have been exceeded.

$$\Omega_E = GR \cdot \Omega_P \quad [9-31]$$

The Mach number in the propeller tip is an intermediate result that allows to evaluate the validity of the assumptions on the model, but which is not used for any other calculations. It is computed with the following expression:

$$M_T = \frac{\sqrt{V^2 + \left(\Omega_P \frac{D_P}{2}\right)^2}}{a} \quad [9-32]$$

The power coefficient of the propellers is computed directly from the advance parameter, with function $C_P(J)$ being itself an input of the model:

$$C_P = C_P(J) \quad [9-33]$$

The aerodynamic power required by each propeller is evaluated from the definition of the power coefficient:

$$P_P = \rho \left(\frac{\omega}{2\pi}\right)^3 D_P^5 \quad [9-34]$$

The total power aerodynamic power required by all the propellers is computed by multiplying the corresponding value of a single propeller by the total number of propellers:

$$P = P_p N_p \quad [9-35]$$

The following step considers the mechanical power loss in the transmission between the engines' output and the propellers' axes. The power at the engine output is computed as follows:

$$P_E = \frac{P}{\eta_T} \quad [9-36]$$

The derivative of weight can be computed from the specific fuel consumption, which is the magnitude that relates the power at the output of the engine (which is required to keep the aircraft in its flight condition) with the consumption of fuel (which is the only mass lost in flight):

$$\frac{dW}{dt} = -c_{pw} P_E \quad [9-37]$$

By following the previous steps, the calculations corresponding to one step are completed. This allows to obtain all instantaneous variables at the corresponding point of the flight. Then, the aircraft weight is updated, and the following step is conducted, with this process going on until the fuel available for the mission segment has been expended.

(e) Sensitivity analyses

The aforementioned schema allows to obtain the performance characteristics of a given RPA, both through its mission space as represented by the combination of PL , R or E , and V or C_L , depending on whether the mission segment is defined in terms of range or endurance, and on which flight law is chosen. In the following subsection, this schema shall be applied to a synthesis problem instead of an analysis one. As it will be expounded then, in that case, the inputs shall be the combinations of values of PL , R or E , and V or C_L which describe the desired missions, along with some other parameters. From this, the geometry of the aircraft that can achieve those design missions shall be obtained.

However, it might also be significant to study, for a given RPA, how small changes in its design features might impact its performance. These kind of studies are recommended in the field of conceptual design, not only to see how design deviations might affect the aircraft's behaviour, but also to understand which variables have a higher impact on the resulting performance (8). Furthermore, studying possible variations in performance due to certain operational aspects, such as the reserve fuel fraction, might also be desirable, as the PL-R and PL-E diagrams also depend on such aspects.

The rationale of the calculation process shown in Figure 9-5 and the computation diagram shown beforehand in Figure 9-8 can be adapted to such cases to perform this type of studies. Instead of the input of the process being a 3-dimensional array of PL , TF , and V or C_L values, the third dimension is substituted by the corresponding design or operational variable which is sought to be studied, for instance, C_{Do} or α (reserve fuel fraction). In this case, the flight law is kept at the same value for all calculations. Then, the computation diagram of Figure 9-8 is run one time for each value of the sensitivity variable that is being analysed. With this, a graphical representation similar to those commented beforehand with the contour of the PL-R and PL-E diagram can be obtained. In this case, the focus would be more on the way in which the envelope itself changes rather than in its content. The results from the application of this sensitivity analysis process shall be shown in section 9.5.

9.3.2. Initial sizing approach for multi-Role RPA

The previous subsection has expounded the novel rapid performance estimation process for multi-mission RPA. As seen in the initial schema of Figure 9-2, this is a fundamental step towards developing the novel multi-role initial sizing methodology which will be developed herein. The envisioned procedure follows an inverse approach to the analysis method: instead of entering with the descriptive data of the aircraft, such as geometry and drag polar, and calculating its performance; here, the inputs shall be a set of design missions which the aircraft must accomplish, and the outputs will be the geometric definition and other defining features of an RPA concept which can succeed in performing all design missions. As seen beforehand in 9.2, the development of multi-role design methods for RPA has not been tackled beforehand within the state-of-the-art. Therefore, the approach presented here, which seeks to address OBJ.3.3 of the thesis, can be considered one of the novel contributions of this research.

Furthermore, one of the main objectives of this method is that it can also aid the designer in the task of the requirements analysis, which was commented in 2.1.2 to be one of the essential steps of conceptual design (10; 11). This consists in studying the ways in which the specifications have an impact on the resulting aircraft. In this context, the study of design drivers is crucial, which are considered to be those requirements which have the most amount of influence on the conceptual design definition. Within this methodology, where various missions with differing requirements shall be defined, perhaps there is one that causes the most significant changes in the resulting design. Therefore, the methodology should allow to study the way in which each mission influences the resulting RPA initial definition, as this can be key towards negotiations with the entity proposing the requirements, which is also a key aspects of conceptual design (11).

Before moving forward, and considering that the performance estimation model is one of the main components of the multi-role sizing approach to be developed here, it is noted that the hypotheses and assumptions employed when developing the previous model also

apply here. This shall be supplemented in the text below, where the modifications which affect the performance method will be highlighted, as well as additional remarks and hypotheses affecting the synthesis approach to be developed here.

(a) Main rationale behind the multi-role initial sizing methodology

As mentioned beforehand, the purpose of the methodology presented here is to start from a series of mission specifications, and through a systematic design workflow, to arrive at an initial conceptual definition of the aircraft. Therefore, setting the inputs of the approach is the first step in the development of this design approach. These have been selected among aspects that can be used to describe typical RPA missions which can be adapted to the flight profile proposed in Figure 9-7. Within the boundaries of the methodology, the purpose is to provide the designer with a high degree of flexibility to define different missions. For this case of multi-role RPA sizing, the following dimensions can be modified by the designer as independent design inputs for each design mission:

- **Payload (PL):** the mass of the equipment used to perform the mission.
- **Range (R) or endurance (E):** the operation can be defined in any of these terms, attending to the degree of freedom allowed by the mission segment commented beforehand. Endurance-based missions shall be more common for reconnaissance roles and similar endeavours, whereas range-based missions might be more usual for payload transportation objectives, for instance.
- **Flight law and value of V or C_L :** the flight law during the mission segment must be defined, as well as the value that the corresponding variable shall take during that part of the flight. Different missions might require distinct flight laws, depending on which is more convenient, and they can also have dissimilar values of the flight variable.
- **Flight altitude (h):** depending on the type of mission and the payload, different flight altitude values might be required.
- **Ingress-egress distance (R_{ineg}):** the ingress and egress range for diverse missions may vary, as seen in (117; 420) among other sources. Thereby, this degree of freedom has also been integrated in the method. It is noted that in all cases the flight law in this segment is that of constant C_L , and the value of this variable is selected following the same procedure as mentioned in the preceding subsection.

The combination of the aforementioned values represent different design mission points in the PL-R and PL-E diagrams. However, it should be noted that not all of them might be visible in the same representation. For instance, if the value of airspeed changes, the points would be at different diagrams along the third axis as seen in Figure 9-5, and thus

not visible at the same time. In any case, all of the missions defined by the designer must be accomplished by the aircraft.

The usual process followed by previous authors for integral performance-based sizing, as mentioned in 9.2.6, is to estimate the mass of the aircraft required to fulfil a design mission, using the integral performance equations to obtain the relevant mass variables from mission parameters (7; 8). This mass estimation usually includes the *FW* and the *TOM* required to carry a certain *PL* up to a certain range. For a single design mission, which is the usual scenario in the literature, the design mission usually sets the value of *MTOM*, so as to design the aircraft to accomplish it, but at the same time to avoid oversizing it, which would reduce its efficiency for the missions inside the diagram (412; 415; 416). These aspects were commented through section 9.2.

However, to obtain the relevant mass variables from the integral performance equations, more data is required, including the drag polar coefficients of the aircraft, and depending on the equations which are required to be used, certain parameters such as S_w may also be needed. This was seen in Figure 9-4, where the different curves in the PL-R or PL-E diagrams are a function of variable such as the drag polar coefficients. In previous works, these are usually selected from typical values of similar aircraft. This then requires, when further design steps have been finished, to iterate on this step, since the drag polar of the aircraft obtained from its geometry when the latter is defined might be different to that which was assumed at this step.

Therefore, it is seen that to tackle this kind of sizing approach, several couplings must be observed. In order to obtain the drag polar of the aircraft, an estimation approach such as those mentioned in 9.2.3 would be required. These models usually define the different coefficients as a function of geometric and flight characteristics of the aircraft, so to perform this step, the geometry is first needed. However, geometric data is not typically among the set of initial specifications, so this information must be provided by another step of the design method. At this conceptual design stage, this process is usually addressed through the use of empirical relationships and typical values from similar aircraft, so as to then move on in later stages to more accurate models once the aircraft has a higher level of definition (7; 8). In the case of this thesis, this can be done through the statistical relationships as extracted in chapter 7, using either the regressions or the factor analysis approach. In both cases, the starting point was the value of *MTOM* of the aircraft, and from this initial input and through the use of the statistical expressions, several variables related to the geometric dimensions of the different components are obtained. However, at the same time, the value of *MTOM*, in many cases, would not be an initial specification itself, as it was commented in the aforementioned chapter. Rather, the inputs given by the designer would be a set of missions that the aircraft must accomplish.

However, a mission-based mass estimation would provide the connection with the aforementioned geometric sizing approach, as it is possible to derive target mass values from the required missions as commented above. This returns to the issue related to the

fact that this mass estimation method would require information such as the drag polar for its computation, with the polar itself being determined from the aircraft's geometry through a parametric estimation approach as commonly done in conceptual design approaches. Considering all of this, and in view of the dependencies among the different steps mentioned above, it can be seen that an iterative approach would be needed to arrive at a consistent aircraft definition that also complies with the requirements.

With this, a simplified schema of the design methodology to be developed in this chapter, consisting in three steps based on the topics mentioned beforehand, is shown in Figure 9-9.

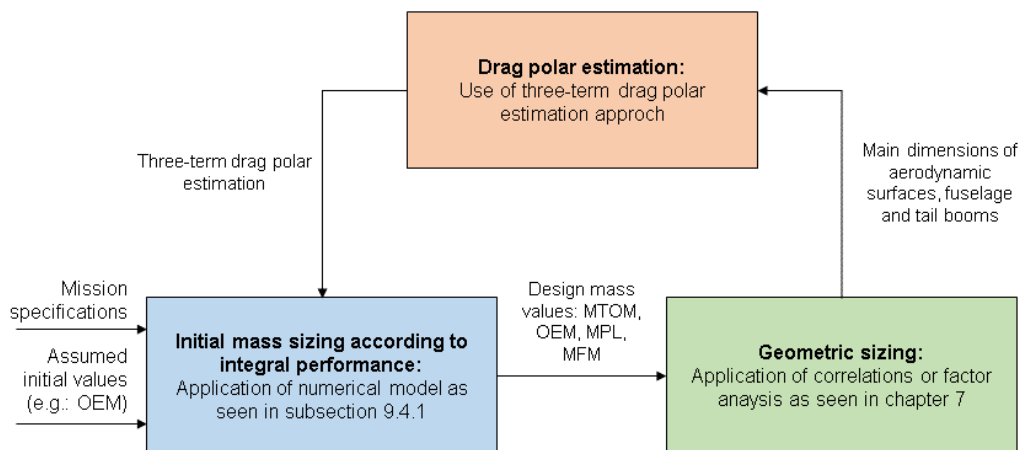


Figure 9-9. Schematic representation of the proposed design loop for integral performance-based conceptual design, with three main steps.

It can be seen that here, the method developed in this chapter integrates the statistical relationships extracted along chapter 7. This is part of the connections among the different standalone design approaches as envisioned in chapter 6.

In the schema provided above, it can be seen that an initialisation of certain values is required to start the design loop. This does not only include the coefficients of the drag polar, but also certain values such as the *OEM*, as the performance characteristics, and thus the curves of the PL-R and PL-E diagram, also depend on other parameters such as these ones. However, in the design loop, these values shall then converge to the final solution which complies with the mission requirements. At the same time, if initial values are provided which would correspond to an aircraft that is oversized with respect to its envisioned design missions, the process shall iterate until the design complies with the required operations without as large a margin, to avoid producing an inefficient design, following the findings of previous works such as those of (412; 415; 416) as commented in 9.2.6.

These kind of iterative convergence loops provide a systematic way to tackle the design problem when the analyses are coupled, such as in the case mentioned above. Furthermore, this kind of procedure can be implemented in a computer program in a relatively direct manner. They are common in conceptual design approaches and also in computerised design environments, as seen in both (41) and (17) among others.

Some additional comments about the initialisation of the design process are outlined below:

- **Initial mass values:** in particular, the *OEM* is required to estimate the corresponding performance of the aircraft in the initial steps. The designer can chose a value from similar aircraft as this starting point. In any case, the mass estimation step shall then iterate over this variable to ensure that the aircraft is both consistent with other design mass values.
- **Initial selection of aerofoils, engine, and propeller:** furthermore, the designer also selects the type of aerofoil used (which influences the profile characteristics and drag curve), the engine equipped on the RPA (with an impact on C_{pm} and limitations related to angular velocity), and the propeller (which detetermines the form of the C_T , C_P , and η_P curves, and also influences certain limitations related to the propeller). This kind of process has also been employed in previous conceptual and preliminary design endeavours (17; 35; 41; 61). If required, the design loop can be run different times while varying these decisions.
- **Selection of layout:** as mentioned in the objectives of this chapter within 9.1.1, and so as to further advance in addressing one of the main gaps in the current state-of-the-art of RPA conceptual design methods, the possibility of sizing different configurations shall be considered. This aspect is mainly related to the geometric sizing step, as the empirical relationships obtained in chapter 7 are at some points dependent on the RPA configuration. In the full design loop, the designer selects the desired configuration in the first place, but a comparison between different ones can be done by running the rapid sizing approach various times for distinct layouts. This possibility shall be further explored in chapter 10.

In the text below, each of the steps shall be commented, with a special emphasis in the initial mass sizing, as it is the one most related to the content of this chapter and where additional considerations with respect to other chapters have been incorporated.

(b) Mass sizing performance-based approach

The mass sizing performance module is the first to be conducted after the initial specifications are established by the designer at the beginning of the process. However, as commented beforehand, an initialisation of some other values relative to the aircraft to be designed is required as an initial guess so as to mathematically close the equations. These will be updated following those obtained in within the design loop at each cycle.

The main idea of this step in the overall process is similar to that followed by previous authors in the aircraft design area, such as Roskam (8). From the initial specifications relative to the integral performances, and using some estimates of certain parameters, an initial estimation of key design mass variables of the aircraft is carried out. The main objective of previous works is to know how much fuel is required to accomplish the design mission, and to link this value with relevant design mass variables such as the *MTOM*.

Figure 9-10 illustrates the classic approach for initial mass estimation based on integral performances used by various previous works, as well as the procedure followed in the methodology proposed here. Their principles and comparison are explained in detail below.

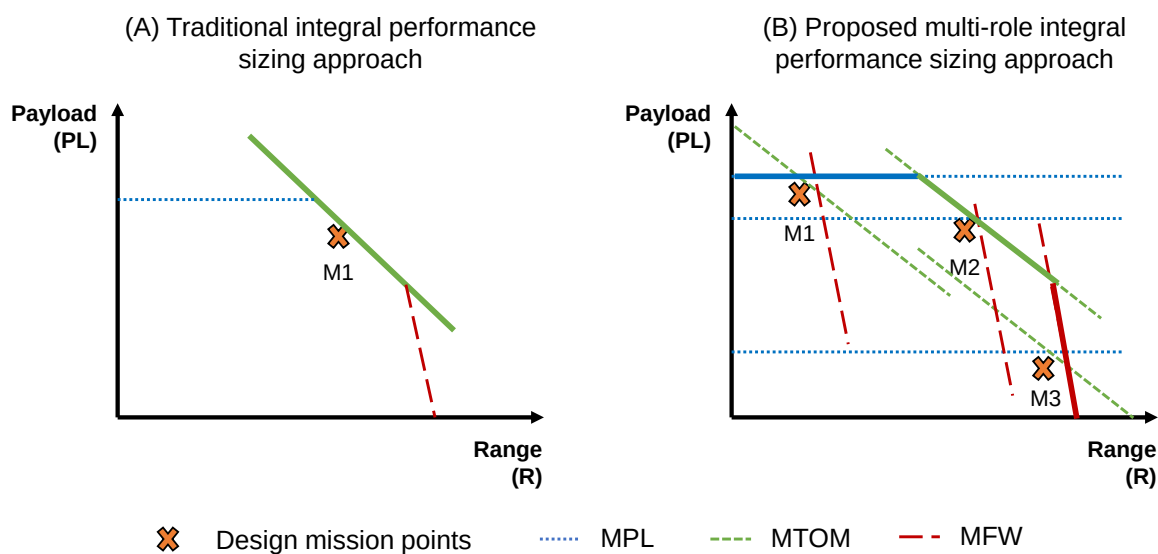


Figure 9-10. Approaches for integral performance-based mass estimation. (A) represents a traditional single-mission approach, as followed in many classical references. (B) illustrates the procedure to be followed within this thesis. The continuous lines represent the final closing envelope of the diagram, which are selected in the multi-role approach as the combination of cases so that every mission point is covered, while avoiding an oversized diagram.

In classical initial mass estimation procedures for transport aircraft, such as those followed by (8; 9), there is a single design mission, and the purpose is to estimate initial values of the aircraft mass values which allow to accomplish it. This procedure is illustrated in Figure 9-10(A). As it can be seen, this type of process usually only estimates the *MTOM* value that is required to achieve the aforementioned mission. Typically, the value of *OEM* is also obtained through a regression with *MTOM*. However, these procedures do not consider other potential missions that the same aircraft must be able to accomplish. Furthermore, usually the *MFM* and *MPL* are not estimated at this stage, since the first value depends on wing sizing, and the second is related to a compound considerations related to fuselage sizing, passenger seat configuration aspects, and structural design.

In the multi-role sizing process proposed in this thesis, the underlying idea is that a set of missions is defined by the designer. These operations have five degrees of freedom as mentioned beforehand. In the illustrative example within Figure 9-10(B), only a single PL-R diagram has been represented, but the missions could be located in diagrams related to different flight laws, altitudes, or R_{ineg} values. Here, the purpose is to obtain an initial estimation of the distinct design mass values of the aircraft, including the values of MPL and MFM , since these determine the contour of the mission space along with $MTOM$, and thus they might be crucial to ensure that all specified operations fall within the diagram.

Firstly, it is noted that the position of the different iso-curves, as well as that of the diagram limitations, are influenced by several variables as given by the integral performance equations commented in 9.2.4. One of these variables that influence the envelope of the diagram is the OEM . The underlying idea of this approach would be to obtain the values of PL_i , TOM_i and FM_i corresponding to each of the design missions. In the diagram, these values can be represented following the schema shown beforehand in Figure 9-6. These three variables are represented in the case of Figure 9-10 here as a set of three curves each corresponding to a particular design mission.

Considering that the purpose is that the final PL-R and PL-E diagrams of the RPA include all design missions within their envelopes, the most restrictive curve for each of the three variables is selected. Following with the illustrated example, the critical case for PL would be the value corresponding to mission 1, PL_1 ; whereas the outer curve for $MTOM$ is the one of the second mission, $MTOM_2$; and in the case of MFM , the limiting case is given by MFM_3 . It could be the case that a single mission is critical in terms of two design masses or even three, and there might also be missions which do not determine any design mass. In any scenario, this process seeks to achieve a diagram that encloses the points corresponding to the design missions so that they are among the feasible operations, but without leaving too high of a margin with respect to these points, in order to avoid an oversized design. Some additional comments in this regard are given afterwards.

This process does not only allow to obtain the design mass variables of the RPA, with these being $MTOM$, MPL , and MFM , but it also keeps track of the corresponding values of PL_i , TOM_i and FM_i for each mission. Since the most critical case for each of these variables is then what determines the corresponding design mass, knowing this information can be of significant value to the designer in terms of requirement analysis and design driver evaluation, which are aspects to be covered by the methodology proposed here. This is because this information can allow to see which missions are more restrictive for each of these design mass values, so that if a certain operation is enlarging the aircraft by a significant amount, the requirements may be negotiated if possible to seek the possibility of a more efficient design.

To obtain the values of PL_i , TOM_i and FM_i for each mission, the following steps are followed:

- 1) **PL_i** : this value is obtained immediately from the specifications for each mission, and in the diagrams it corresponds to a horizontal line passing through each point.
- 2) **FM_i** : for each mission, since the desired range or endurance are known, the purpose is to obtain the fuel mass which allows to accomplish the specifications. An iterative process is followed by applying the computation process previously illustrated in Figure 9-8 for the value of payload of each mission and changing the value of FM_i in each iteration, until convergence is reached to a value of R or E that satisfies the mission. It is noted that the value of OEM is required to solve the diagram's process.
- 3) **TOM_i** : having obtained FM_i and from the OEM , PL , and RF , the take-off mass can be computed.

With this, comparing the values of the aforementioned mass variables for each mission, and following the criteria illustrated in Figure 9-10, the global aircraft values of $MTOM$, MPL , and MFM are obtained.

As it can be seen, the value of OEM which is given by the designer among the input initialisation is required to solve the aforementioned steps for each mission. However, there is no guarantee that the obtained values of $MTOM$, MPL , and MFM are consistent with this initial value of OEM , particularly if the reference aircraft from which its initial value of was obtained are very distinct to the one which is being designed. In order to check this consistency, from the database compiled in the work related to chapter 7, a regression has been obtained which allows to obtain OEM .

One of the predictor variables has been chosen to be MPL , since if the payload which has to be carried by the RPA increases, it can be expected that the airframe will need to be larger to accommodate it. Furthermore, this allows to account for the effect of this input from the designer on the resulting empty mass of the aircraft. Then, another predictor variable is selected to be MFM , since the additional fuel is also related with a general increase in the aircraft size (11), and in the case of existing RPA the fuselage tanks are often located in the fuselage, resulting in an additional increase in its size (1; 37). Additional points substantiating the selection of these two variables are given further below. The resulting multiple regression with these two variables is shown in Figure 9-11.

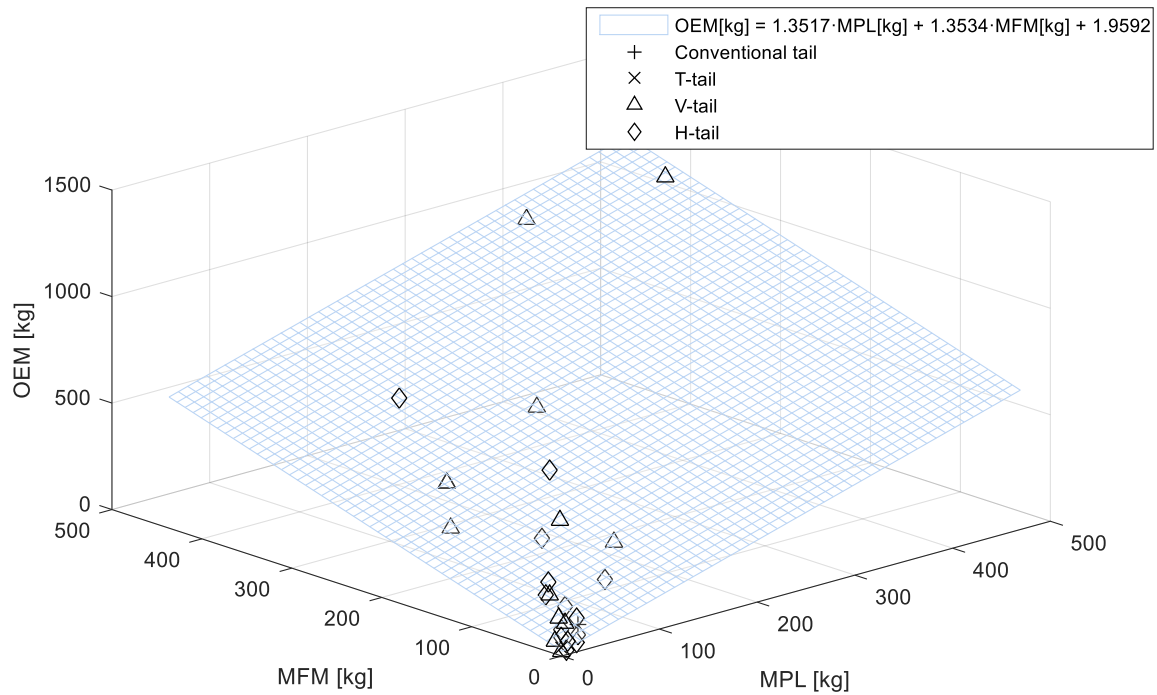


Figure 9-11. Multiple linear regression of $OEM - [MPL, MFM]$ for conventional tail, T-tail, V-tail, and H-tail RPA with reciprocating engines. $\bar{R}^2 = 0.9461$, $RMSE = 68.26$.

From the scatter points, it can be seen that there is not always a simultaneous increase in MPL and MFM , since both payload-dominated vehicles as well as performance-dominated ones can be found within the database. In this way, RPA can be seen with high values of MFM but comparatively lower ones for MPL , while in other aircraft, the emphasis is on MPL whereas the value of MFM is lower in these cases. These two distinct effects, which would not be seen separately with a regression only with $MTOM$, are accounted for through this approach. It is worth pointing out, as it can be seen from the coefficients of the regression, that an unit increase in both MPL and MFW have both a very similar effect on the resulting growth of OEM . In any case, keeping the effect of both variables separate constitutes a significant prospect, since if a vehicle is to be designed that seeks to achieve both payload-dominated and performance-dominated operations, even in different design missions, its empty mass will be penalised by the combined effect of both components. Furthermore, and particularly considering the fact that missions with very disparate specifications can be introduced in this methodology, keeping both effects separate allows to quantify how much the empty mass of the overall vehicle is being influenced by each of these dimensions, following on the topic of requirements analysis which is emphasised through this methodology.

If the value of OEM obtained through this regression does not match, up until a certain tolerance, the one that was initially given by the designer, and so as to ensure the consistency of the design mass variables of the aircraft, the process loops back to the start by updating the value of OEM with the one obtained by the regression. This leads to a new

iteration where different values of $MTOM$, MPL , and MFM are obtained, and the workflow would continue to loop until a convergence in OEM has been achieved. This process, which corresponds to the first of the three steps of the full design methodology, is illustrated in Figure 9-12.

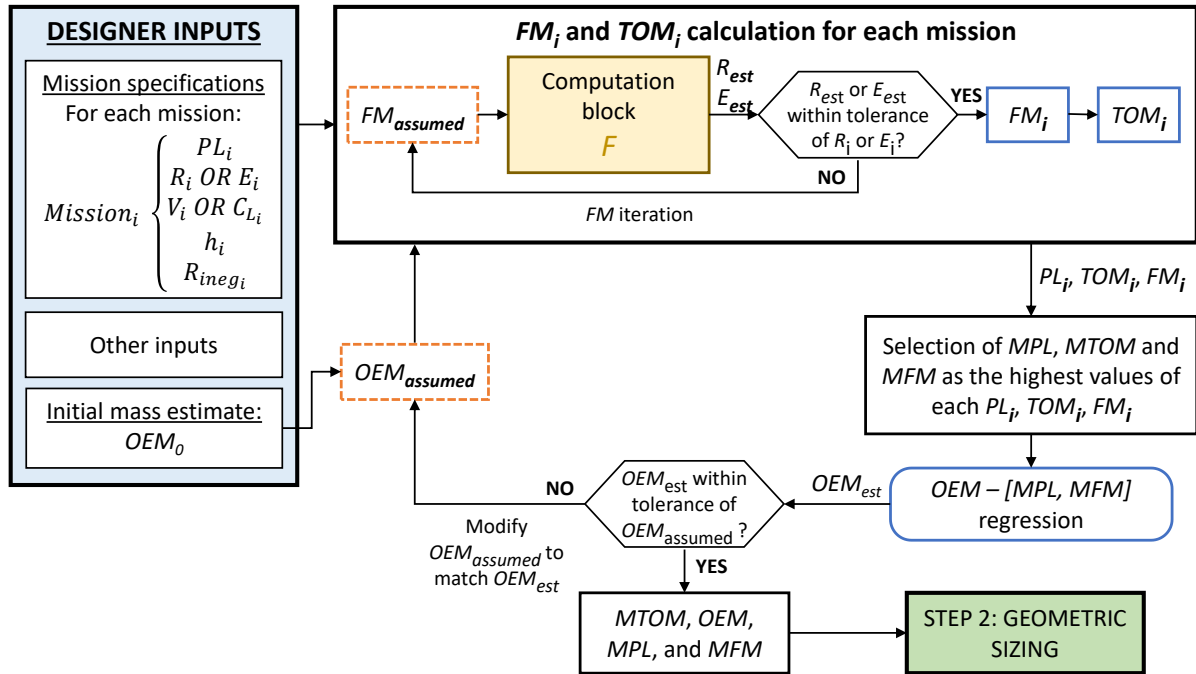


Figure 9-12. Workflow of the mass estimation step of the proposed multi-role RPA design methodology.

As it can be seen, this process accomplishes that $MTOM$, OEM , MFM and MPL all have mutual influences in each other through the performance estimation block, the multiple regression, and the iteration loop itself. This procedure has been checked several times and it has been seen that it generally shows a convergent nature for consistent inputs of the process.

With respect to the objective that the PL-R and PL-E boundaries enclose the design missions without too much of a large margin, the purpose is to avoid generating an oversized RPA which is less efficient when conducting operations in points which are located inside of these diagrams, including the design missions themselves. This perspective uses as a basis the findings of the investigations found in (412; 415; 416), as mentioned beforehand. However, it is also noted here that if the diagram was to be enlarged with respect to the design missions, the MPL and MFM would be increased. Attending to the workflow proposed here, this would lead to a growth in OEM , resulting through the loop in additional increases in $MTOM$, MPL , and MFM until the loop converges. This behaviour should be considered by the designer when selecting the design missions, so that they correspond to an array of potential operations so as to ensure that all envisioned uses of the RPA are accomplished, but without giving excessive margins that would result in an inefficient aircraft within its diagram.

(c) Geometric sizing approach

The main outputs from the previous process are the four main design mass variables: *MTOM*, *OEM*, *MFM* and *MPL*. With this, the statistical procedures developed in chapter 7 can be employed, as their main input was precisely the value of *MTOM*, which is representative of the overall size of the aircraft (11; 42). At that point, it was commented that the input of the geometric sizing process did not correspond to an initial specification, but that in later steps of this research, the entry value of these empirical procedures would be connected to RPA initial specifications, which has been accomplished through the preceding mass estimation step expounded in the current chapter.

The designer has the choice of using both the regression-based approach and the factor analysis-based process, with the second one being available only for H-tail RPA, while it requires less additional inputs and is more automatic. The application of these procedures at this point allows to estimate several values related to the geometry of the aircraft, including the main areas of both its wing and tail surfaces, as well as key dimensions of the fuselage (and tail booms if present). The diverse elements of the aircraft: wing, tails, fuselage and tail booms. In chapter 7, the hypotheses, steps, and considerations pertaining to these methods were expounded in detail. As commented there, it is noted that the wing sizing is provided for a straight-tapered type of surface, following the equivalent wing criterion.

The information provided by the aforementioned approaches allows to address one of the main gaps detected in current RPA initial sizing methods, which is that an initial definition of its main components was not covered by many previous works. This, in turn, is required to perform an estimation of the drag polar that accounts for all of these elements, including the contributions of tail surfaces and fuselage.

(d) Drag polar estimation method

The third step in the design process is the estimation of the drag polar of the RPA as a function of its flight conditions and its geometry, with this latter point having been covered by the previous step. This drag polar estimation allows to loop back to the initial assumptions made in the inputs required to the mass estimation step, closing the outer loop of the full design methodology.

There are many approaches to aircraft drag estimation, with differing levels of accuracy and computational cost. As commented in 9.2.2, the most usual technique for conceptual design is the use of manual-like semi-empirical parametric models which allow to obtain the polar coefficients as a function of a simplified definition of the aircraft's geometry. However, it is required to adapt the models that were originally envisioned for manned aircraft so that they can be used for accurate RPA drag estimation. When considering this, these tailored rapid estimation models have shown a satisfactory agreement with CFD and wind tunnel results (53; 61), and they have even been used within optimisation

frameworks where a higher degree of accuracy was sought when compared to that of conceptual design approaches (61).

As substantiated in 9.2.2, and considering the singularities of RPA, a three-term drag estimation model is sought to be used in this design methodology. It is noted that in the performance estimation approach presented in 9.3.1, this drag model to estimate the polar curve from the geometry was not needed, as the drag polar was considered as an input of the process, since the objective was to estimate the behaviour of an already given RPA. In this case, the selected model should allow to obtain an accuracy within the margin of errors of conceptual design, while also requiring few input data, so that it is consistent with the outputs of the geometry sizing step.

The drag polar model used here is mainly based on the one given by Torenbeek (7). The lift-independent drag and lift-dependent drag of both the wing and fuselage have been considered through this approach. Since the definition of the aircraft at the point of the design continuum being considered here does not include its mass distribution, trim drag has been considered outside the scope of this model. However, the lift-independent drag of tail surfaces has been accounted for to complete the drag estimation of streamlined bodies. It is noted that to estimate the friction coefficient, C_f , the value of the Mean Geometric Chord (MGC) of these elements is required. This can be obtained through the information given by the geometric sizing process, complemented with values of aspect ratio and taper ratio from similar aircraft. It is highlighted that the fuselage lift-dependent viscous drag has been considered within the model, which has not been found in previous works within the state-of-the-art of conceptual design within this field.

With respect to the interference drag among the various main airframe components commented beforehand, this shall be considered in the model using Interference Factors (IFs), which is a common approach to include this effect in conceptual design. These have been obtained from references (9; 54) and are summarised in Table 9-2. Furthermore, corrections to dynamic pressure considering wake interactions have also been considered as seen in (54).

Table 9-2. Summary of IFs considered in the drag polar model, based on (9; 54).

Component interaction	IF	Component interaction	IF
Mid-high wing	1.05	T-tail	1.04
Low wing	1.25	H-tail	1.06
Conventional tail	1.05	V-tail	1.03

However, as mentioned beforehand, drag polar estimation methods which have been developed for manned aeroplane should be adapted to account for the singularities of RPA to enhance their accuracy when applied to this field (52; 53). One of the foremost areas in need of tailoring has been noted to be that of bluff body drag estimation. RPA in the small and tactical range are typically equipped with fixed landing gears (53). Furthermore, the payload is an element that usually protrudes from the fuselage and generates significant

drag. Other corrections to account for additional drag sources distinct from those of manned aircraft have also been emphasised. Albeit various drag polar estimation models, such as the one of Torenbeek, include the contribution of landing gears and other elements, the ones used on RPA showcase significantly different geometries when compared to those of manned aeroplanes, resulting in remarkable drag differences (52).

The research conducted by Götten in the recent works of (420; 424) has analysed the drag contributions of elements such as payload bubbles, fixed landing gears, and other bluff elements to the overall drag of the RPA. The geometries studied in these works are representative of those typically found in SMR RPA, which fits with the main range of applicability of the regression model used in the previous step, thus being aligned with the kind of design methodology proposed in this chapter. It is noted that these investigations are mainly focused on the contribution of these types of elements to the lift-independent drag of the whole vehicle, which is included in the C_{D0} coefficient.

Considering the above, the following correction to the lift-independent drag of the whole RPA is proposed here:

$$C_{D0} = \frac{C_{D0_{Basic}}}{1 - \frac{C_{D0_{LG}}}{C_{D0}} - \frac{C_{D0_{PL}}}{C_{D0}} - \frac{C_{D0_{excr}}}{C_{D0}}} = \frac{C_{D0_{Basic}}}{1 - \eta_{LG} - \eta_{PL} - \eta_{excr}} \quad [9-38]$$

Where $C_{D0_{Basic}}$ represents the lift-independent drag of the RPA before applying these corrections, and η_{LG} , η_{PL} , and η_{excr} , each represent the relative contributions of Landing Gear (LG), payload, and other excrescences, to the overall lift-independent drag coefficient. These values can be obtained from the data compiled in references (53; 420), which has been specifically obtained for RPA.

The result is a three-term drag polar that can be then used to conduct the mass estimation of the RPA attending to its mission requirements within a new loop of the design process.

(e) Loop closure and final observations

The outer loop of the design methodology proposed here has been closed with the previous drag polar estimation step. This allows to conduct a new series of mass estimations, and to continue the process until a consistent RPA has been reached. It is considered that the methodology has converged when the value of MTOM between one iteration and the previous one is below 1%. This is significantly below the margin of error usually allowed in conceptual design approaches, but has shown good convergence characteristics in the use cases of this methodology. The use of MTOM as a convergence criterion to close a design convergence loop has also been employed in previous research on conceptual design (41).

At this point, the impact that each mission has on the design can be evaluated through the calculation steps conducted in the mass estimation step, since the values of PL_i , TOM_i

and FM_i corresponding to each design mission have been obtained. Even in the case that the loop does not converge, it can be seen which missions may be causing this behaviour. These findings can allow to set the basis to negotiate and even relax certain mission requirements if this could provide an improvement to the design, or even if certain specifications are leading to non-converging design processes, as commented in previous research on RPA design (77). This is an significant part of the conceptual design process, thus it has been sought to consider it in the methodology proposed within this chapter so as to aid the designer in this task. Some applications of this concept shall be seen in the application case to be developed in 9.6.

9.4. Performance estimation results and discussion: flight law analysis

The above section has presented the methodologies for both rapid performance estimation and multi-role RPA design which are among the research contributions of this thesis. Now, these design approaches shall be employed in various practical cases along the following sections. Here, the performance estimation model developed in 9.3.1 will be put in practice for the study of the two different flight laws that are considered in its modelisation to a particular case of study. This will allow to obtain a substantial volume of information about the aircraft's performance characteristics, which will be summarised through the PL-R and PL-E diagrams and iso-curves as commented when expounding the methodology.

The RPA that will be analysed in this case study is the RQ-2 Pioneer, which was already used as a test case for the geometric sizing approaches developed in chapter 7. In this case, the focus is not on synthesis, rather on analysis, according to the scope of the rapid performance estimation methodology. The data which has been employed in the performance calculations developed through this section is presented in Table 9-3.

Table 9-3. Data of the RQ-2 Pioneer to be employed in the performance estimation case study. Aircraft information obtained from (390; 444; 445).

Input element	Value	Input element	Value
<i>MTOM</i>	205 kg	<i>S_w</i>	3.181 m ²
<i>MPL</i>	45 kg	<i>C_{Lmax}</i>	1.358
<i>MFM</i>	36.3 kg	<i>C_{D0}</i>	0.06
<i>OEM</i>	138 kg	<i>C_{D1}</i>	-0.031
<i>α</i>	0.07	<i>C_{D2}</i>	0.071
<i>β</i>	0.05	<i>D_P</i>	0.73 m
<i>h</i>	500 m	<i>C_{pm}</i>	8.8e ⁻⁸ s ² /m ²
<i>R_{ineg}</i>	90 km	<i>Ω_{Emax}</i>	8000 rpm

The values of the α and β parameters, which are related to mission planning, have been taken from the open literature of RPA design (13) (67), as commented in 9.3.1. The value

of R_{ineg} has been selected according to the RQ-2 Pioneer operations commented in (445). The maximum lift coefficient, C_{Lmax} , along with the coefficients of the drag polar, were obtained from the wind tunnel tests documented in (444).

In the following subsections, each of the two possible flight laws that are considered in the performance model shall be studied, so as to analyse the influence that the choice of one or another has on the PL-R and PL-E diagrams. Before moving forward, it is noted, as commented in 9.3.1, that these diagrams shall be represented in terms of R_m and E_m , as these are of most interest in terms of both design and also operation planning, since the ingress and egress flights are only positioning segments which do not actively contribute to accomplishing the mission itself.

9.4.1. Constant airspeed flight law

Firstly, the constant V flight law will be analysed in this subsection. As mentioned when expounding the performance analysis model in 9.3.1, this methodology allows to analyse the performance characteristics of the aircraft not only through the variation of its PL and either R or E values, but also considering changes in the variable related to the corresponding flight law, in this case, V . For each of the values selected for this variable, different PL-R and PL-E diagrams are obtained, as it will be seen afterwards.

In the literature, values of flight speed for the RQ-2 Pioneer have been found ranging from 28 m/s to 50 m/s (390; 444). Therefore, the sweep to be performed over this variable in this study shall cover the interval 25-50 m/s. Albeit not all of these values correspond to practical flight conditions, covering a wider range shall allow to more clearly represent the ways in which the flight speed changes the integral performance capabilities of the aircraft, as well as possible restrictions which may arise, for instance due to stall phenomena.

Firstly, the overall shape of the diagram is represented for a characteristics value of speed of the RQ-2 Pioneer, which is of 40m/s as given in (390). The diagram has been represented, firstly, for a value of $R_{ineg} = 0$ and for $\alpha = 0$, which corresponds to a mission without accounting for reserve fuel and lacking a positioning flight. Then, another diagram is shown which is according to the data provided in Table 9-3. The results are shown in Figure 9-13.

As it can be seen, the first diagram shows a classic shape, with the three boundaries corresponding to the design mass variables MPL , $MTOM$, and MFM being seen. It is noted that in all graphical representations shown through the remainder sections, the MPL limitation is overlapped with the upper frame of the diagram, and would start where the $MTOM$ curve intersects the frame, which allows to check the presence of the MPL limitation.

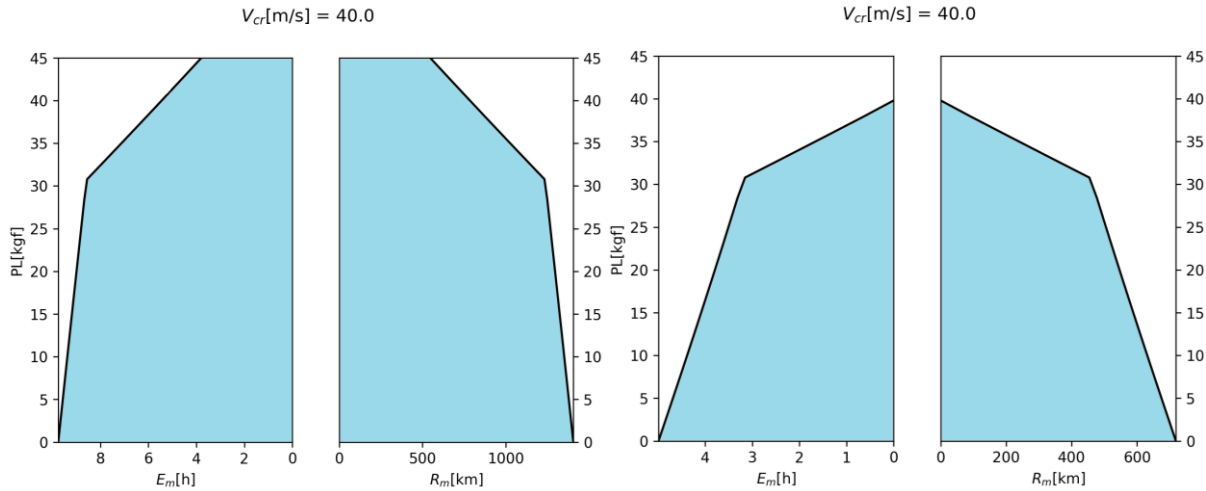


Figure 9-13. The left-hand-side image represents the PL-R and PL-E diagrams for the RQ-2 Pioneer under the conditions of zero α and R_{ineg} . The right-hand-side image corresponds to the diagram but in this case using the case study data.

In contrast, the second diagram shows a distinct shape, where the *MPL* limitation does not appear. This is due to the high impact that the *RF* and the ingress-egress flight has on the performance of the aircraft, as it can be seen in the values of E_m and R_m achieved in each case, which correspond exclusively to the mission segment. Therefore, in the case where $R_{ineg} = 90$ km, there a total of 180 km are being flown by the RPA which do not contribute to accomplishing the mission. This value is around 20 % of the maximum range as seen in the PL-R diagram. Thereby, the positioning segments have a noteworthy influence on the overall performance of the aircraft, which is added to the effect of the *RF*. As a result from all of this, if the aircraft is loaded with its *MPL*, it cannot reach the mission point for the case of an operation with these parameters. However, as seen in the first paragraph, it is feasible to carry this *MPL* in other operating conditions. This showcases the outstanding impact that the parameters describing the mission profile have on the aircraft's performance, which was amongst the reasons to consider these degrees of freedom when establishing the model. Furthermore, this substantiates through a practical case the fact that the PL-R diagram's envelope is also a function of aspects such as the geometry of the flight profile, as brought forward in advance in Figure 9-4. The sensitivity of the diagram as a function of *RF* shall be analysed in further detail within section 9.5.

From now on, the data which has been obtained from the aforementioned references from the literature as shown in Table 9-3 will be employed for the remainder of the calculations. The next step shall be to study the variation of the envelope of both diagrams when modifying V , which as commented beforehand in this chapter has not been typically done in the field of RPA, in spite of their remarkable mission variability. This scenario is is represented in Figure 9-14.

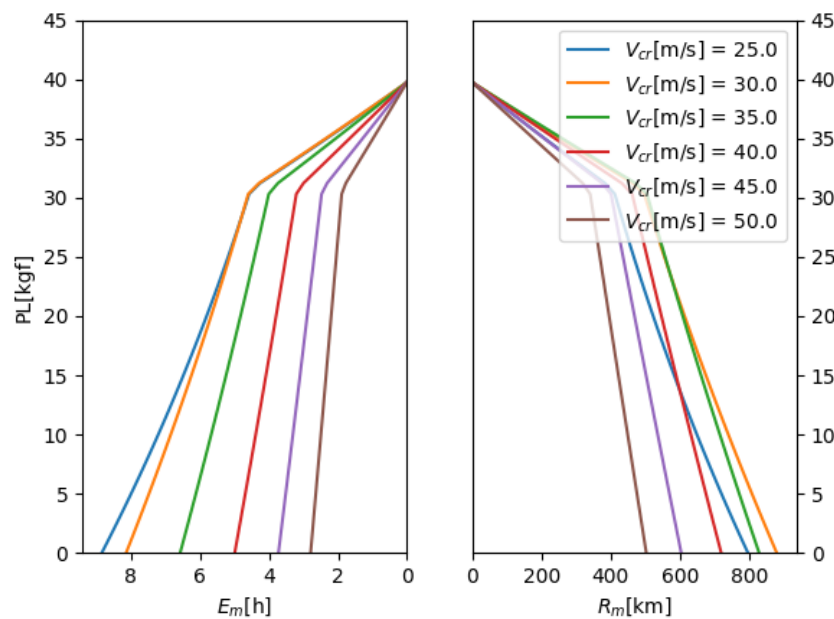


Figure 9-14. Variation of PL-R and PL-E envelopes for different flight speeds for the RQ-2 Pioneer RPA case study.

Accurate values for the endurance of the RQ-2 Pioneer RPA have not been found that are accompanied with their corresponding values of PL and V . However, typical endurance figures listed for this aircraft range from approximately 5 h to 6 h. It can be seen that these values are consistent with various flight speed values in the lower range, where a range of PL mass values can be flown to reach the aforementioned values. This serves to support that the results obtained with this model seem to fall in a reasonable range for the aircraft which is being analysed.

As it can be seen, the flight speed has a very significant influence in the integral performance of the aircraft, thus in values of range and endurance that it can achieve. For instance, the relative difference between the value of endurance when flying at a speed of 40 m/s and that when flying at 30 m/s is of 63 %. It can be seen that adjusting the airspeed of the RPA, significant improvements can be obtained in performance. However, it is noted that, since the diagrams are focusing on the mission segment, the selected flight speed should be compatible with the task that is to be performed at that point of the flight. For instance, speeds that are too high might complicate the data acquisition task by certain sensors. Therefore, these results, as well as the potential benefits in performance that can be achieved by changing the value of V , should be considered in the context of each operation as well as taking into account the possible limitations that should be considered other than those that are purely related to flight mechanics.

It is also highlighted that there is a remarkably different behaviour in the graph's boundary between both diagrams. In particular, in the case of the PL-R diagram, the most

expansive envelope is obtained approximately at 30 m/s, with the surface covered by the diagram diminishing if the speed is further decreased, was seen for the speed of 25 m/s which has a significantly inferior performance. However, in the PL-E diagram, the most expansive envelope is obtained for 25 m/s, at least within the speed interval that was analysed here. This difference between both diagrams can be substantiated through the dissimilar values of the flight C_L that respectively achieve maximum range and endurance, with the second one being higher. Since at lower airspeeds, the lift coefficient is higher, for $V = 25$ m/s the maximum range C_L has already been exceeded in most points of the diagrams, resulting in a loss of efficiency, whereas the value corresponding to the maximum endurance is higher, and it seems to approximately match this flight speed.

However, it should be remarked that using this flight law, the C_L changes along the flight and also through different points of the diagram, so the comments above only represent an outline of the way in which this variable influences the boundaries of the diagram. The accurate behaviour of the lift coefficient is now analysed in Figure 9-15, which shows iso-curves both for the average value that it takes along the flight that corresponds to each position of the diagram, with a second family of curves representing the difference (Δ) between the maximum and minimum value along each flight.

From these results, it can be seen that, save for long endurance or range missions, the variations shown by C_L along the flight are not particularly remarkable. However, the average value of this variable can change up to 20% along different points of the same PL-R or PL-E diagram. The average C_L required in the flight rises as the value of PL increases, which can be expected as a larger weight will require higher values of C_L . This variation of C_L along the diagram can explain the behaviour seen previously in Figure 9-14, where sometimes the different envelopes cross each other. This is due to the different value of C_L through the envelope, which may result in the upper region of $V = 35$ m/s showcasing a value of lift coefficient closer to the one of maximum range than the one corresponding to the diagram of $V = 30$ m/s, whereas the trend is reversed when focusing on the lower region.

When changing the flight speed at which the diagram is obtained, there are remarkable variations, as seen in the $V = 25$ m/s case. Here, the variations of C_L along the flight are more noteworthy, and more importantly, the average value of C_L reaches values corresponding to stall through most of the region defined by the diagram. To truly pinpoint the region of unfeasible missions where stall occurs at some point of the flight, the iso-curves for the maximum value of C_L along each flight would have to be represented, but overall and due to the proximity to stall, it would not be recommended to conduct operations in the points of the diagrams corresponding to this flight speed.

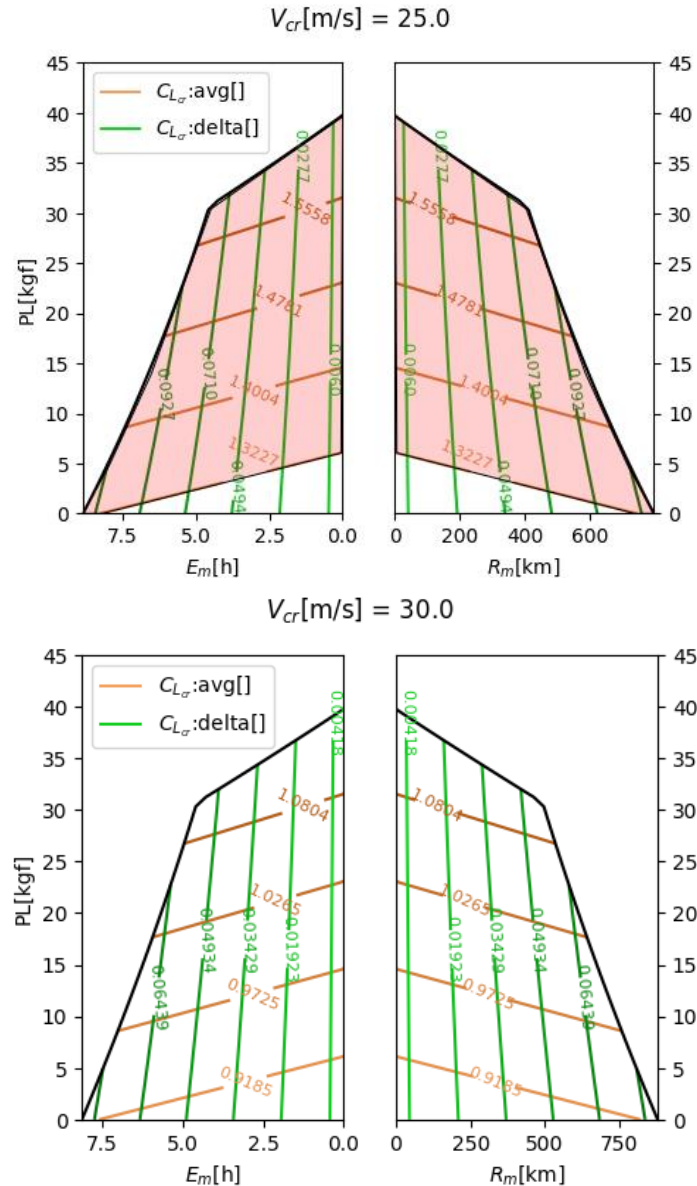


Figure 9-15. Iso-curves for average C_L value along the mission stage and for the difference between the maximum and minimum C_L value also along each flight, represented for different flight speeds corresponding to the RQ-2 Pioneer RPA case study. The approximate region representing missions where stall happens at some point along the flight has been highlighted in red.

Now, in Figure 9-16, the iso-curves corresponding to the TF and FW variables are represented. These correspond to integral variables, thus there are no variations along the flight, in contrast to the previous case. It is seen that, when focusing on a particular coordinate point of the diagram (PL, R) or (PL, E) , which represents a specific mission, the difference between both mass values is noteworthy. This is due to the value of $\alpha = 0.07$ which was used as an input data. This fraction of reserve fuel can be justified for usual operations, as the RQ-2 Pioneer RPA is typically recovered via conventional landing on runway or with a net, so a certain quantity of contingency fuel would be required. This is due to the aircraft not being as flexibly recovered as other RPA which might have the

capability to use a parachute, or even for small RPA, the possibility of conducting a belly landing. The geometry and behaviour of the iso-curves at different values of V is similar, albeit the ones for the lower figure present a slightly more noticeable curvature, following the trend also observed beforehand in the diagram's boundaries as seen in Figure 9-14. This can be expected when considering that the FW iso-curves constitute a general representation of the particular one corresponding to MFW .

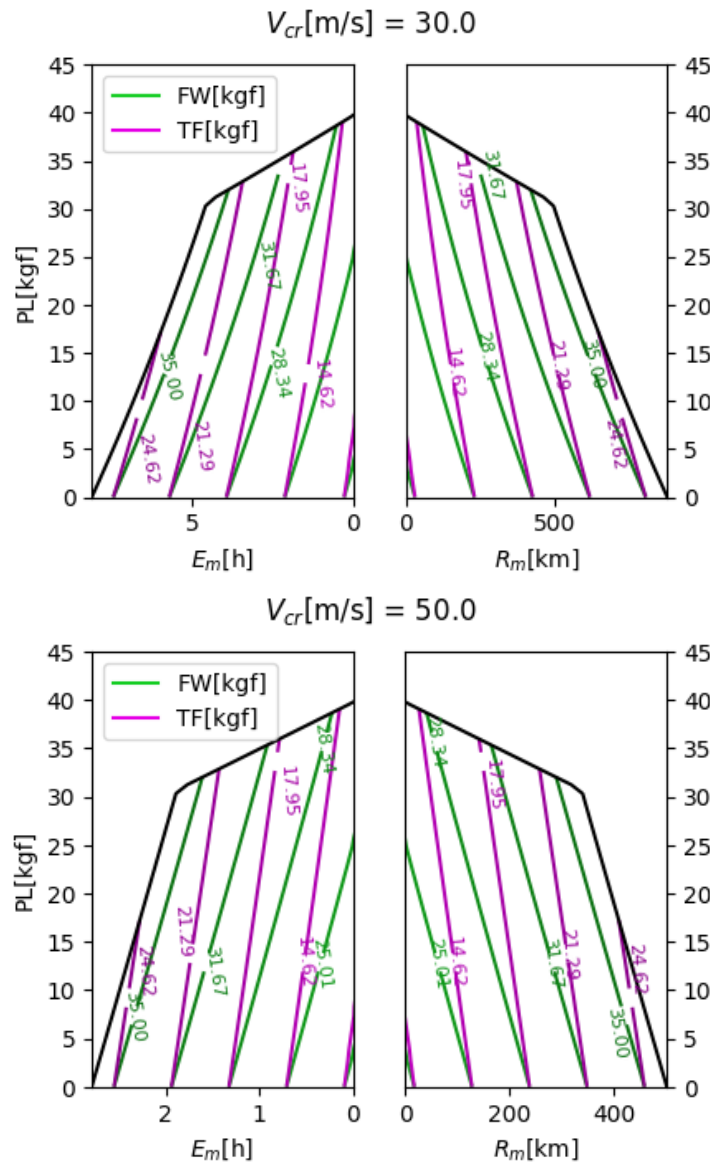


Figure 9-16. Iso-curves for TF and FW for the Pioneer at two different flight speeds.

In a similar way, the iso-curves representing the variations in TOW and LW along the diagram are shown in Figure 9-17. The expected behaviour of the TOW mass curves was already commented in Figure 9-6 during the methodology development. The results found here fit the anticipated trend, with the curves being mostly parallel to the $MTOW$ limitation. With respect the landing mass ones, they are coherent with the RF formulation

used in this thesis, which only depends on the OEW and value of PL , thus resulting in the horizontal lines seen in the graphs.

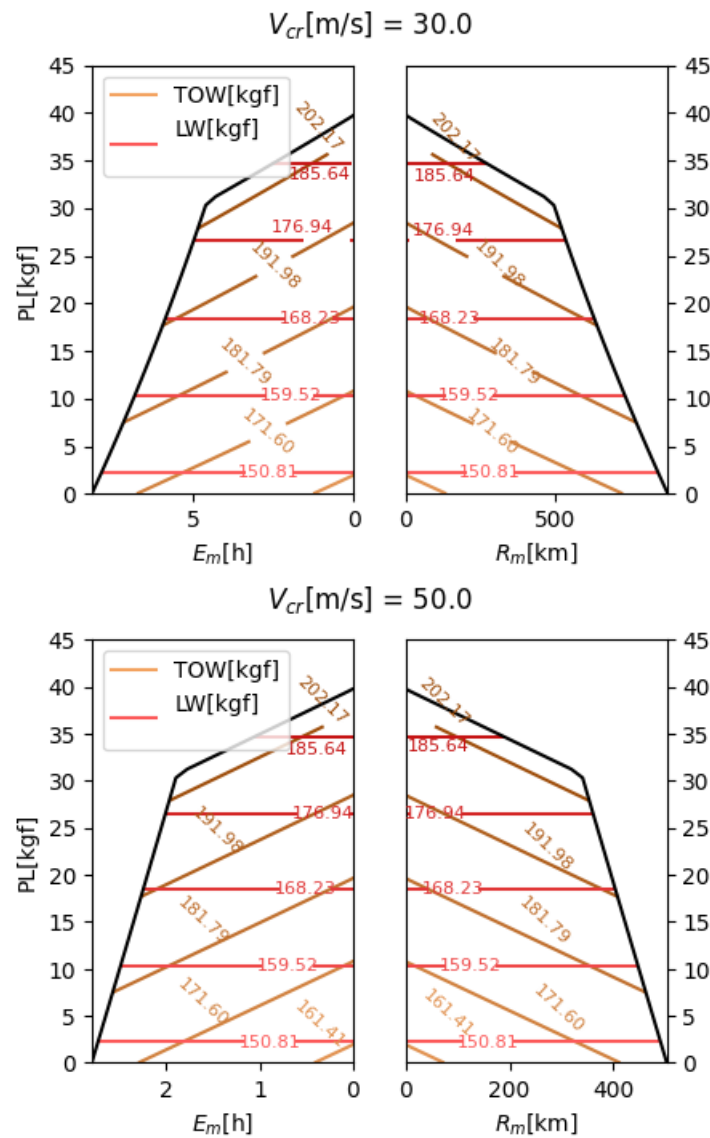


Figure 9-17: Iso-curves for TOW and LW for the Pioneer at two different flight speeds.

As commented in 9.3.1, one of the main strengths of the model is that it can also obtain the changes in certain variables related to the powerplant, which has not been analysed beforehand in the field of RPA conceptual design. Thus, the variations in the average value of Ω_E , as well as the delta value along each flight, are represented in Figure 9-18.

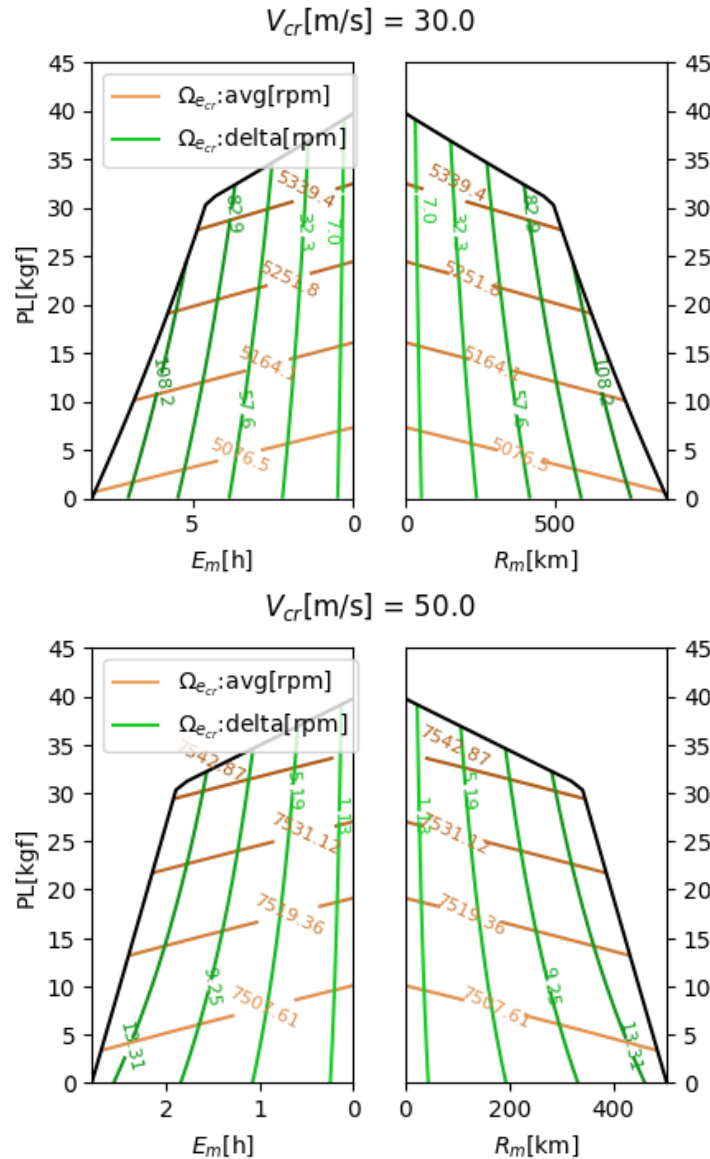


Figure 9-18. Iso-curves for both average Ω_E value and its delta along the mission stage, for different flight speeds corresponding to the RQ-2 Pioneer RPA case study.

As it can be seen, the revolutions of the engine augment considerably when flying at closer to the maximum flight speed of the RQ-2 Pioneer. In contrast, the variations in engine revolutions along the flight are more noticeable at lower flight speeds. This representation does not allow to directly monitor the maximum value of Ω_E in each flight, but compounding both curves it can be seen that in no case the values exceeded the maximum Ω_E of the engine as seen in Table 9-3. However they are relatively close to its value, which is consistent with the fact that this is the highest value of the flight speed interval found for the RQ-2 Pioneer. With angular velocity values of the engine this close to their maximum, it would be worth to monitor the propeller tip speed. With this, Figure 9-19 represents the iso-curves corresponding to the maximum values along each flight of

both Ω_E and the Mach number at the propeller tip, M_{ptip} . This allows to analyse in a more direct manner the possible limits that might arise with respect to these two variables.

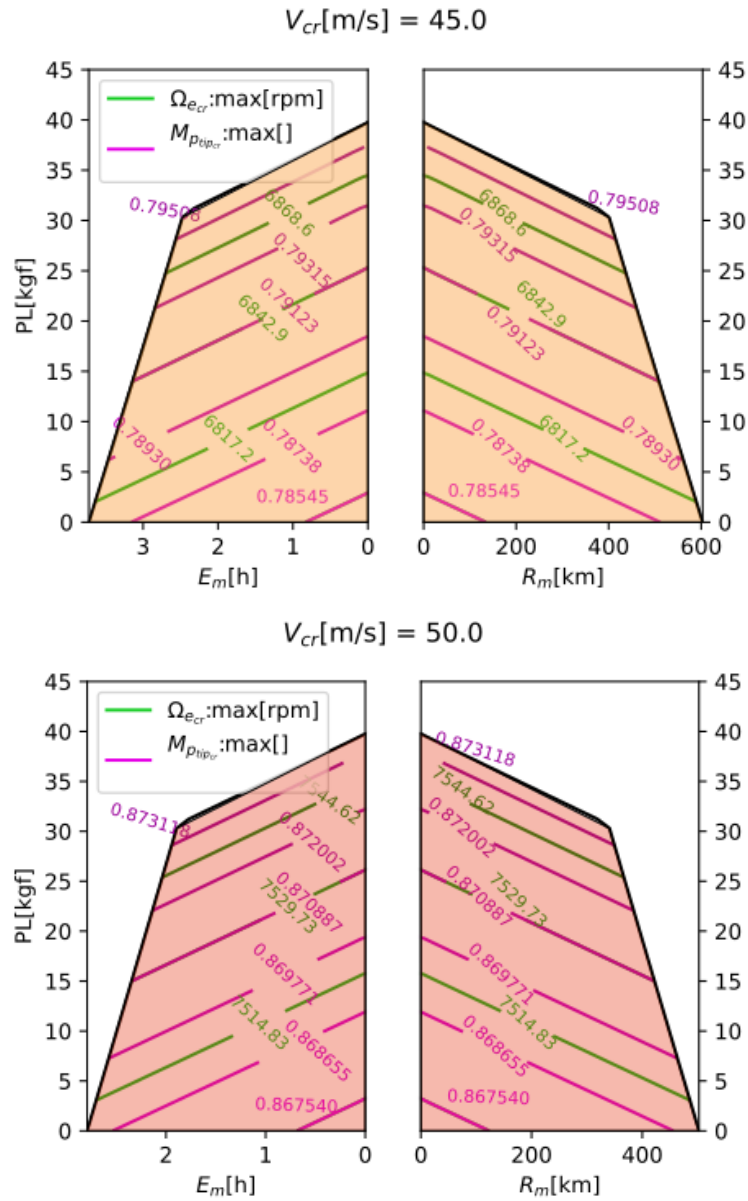


Figure 9-19. Iso-curves for maximum Ω_E and M_{ptip} along the mission stage, represented for different flight speeds corresponding to the RQ-2 Pioneer RPA case study. The region where noise issues might appear due to the propeller angular velocity is highlighted in orange, and that where transonic effects occur is marked in red.

With respect to these two families of iso-curves, it is noted that they are both parallel to each other and approximately to the $MTOW$ limitation. This is in contrast to the previous average Ω_E curves, which had a lower slope, as it is seen when comparing with Figure 9-18. This difference is due to the maximum Ω_E curves corresponding to a combination of those of the average Ω_E with the delta ones.

As it can be seen, even though the engine still has a certain margin with respect to its maximum value of Ω_E in all flight conditions analysed here, the values of M_{ptip} are remarkably high. With respect to the maximum allowable values of this variable, references (7; 406) state that, over values around 0.85-0.90, transonic effects appear in the propeller blades and there is a significant drop of their performance, making the C_T , C_P , and η_P curves as obtained for regular flight conditions no longer applicable. On the other hand, in (6) it is stated that 0.72 is a recommended maximum value when taking into account noise considerations. In view of this, already for $V = 45$ m/s, the noise recommendation would have been surpassed, which might constitute an issue especially when conducting certain ISR operations with this RPA. Furthermore, the case of $V = 50$ m/s would already fall within the potential limit of validity of the propeller model, which might imply that the RPA's performance at this flight speed could be lower than that which has been obtained here. This reinforces the notion that this value of V corresponds to the maximum flight speed of the RQ-2 Pioneer, as supported by the data found in the literature.

Overall, the model predictions seem to be in accordance with the data of the Pioneer in terms of endurance, maximum airspeed, and other values as obtained from the cited references (390; 444), thereby supporting the validation of the rapid performance estimation model. The possibility to evaluate the ways in which different integral and instantaneous variables are modified through the diagram provides a substantial amount of data with respect to the aircraft's performance capabilities. This includes the possibility of detecting unfeasible mission regions where certain limitations are exceeded.

9.4.2. Constant lift coefficient flight law

The constant lift coefficient flight law has already been employed in previous works pertaining to the the field of RPA conceptual design (6; 17; 151), albeit up until now the analysis of their influence on the PL-R and PL-E diagrams has not been undertaken, and neither a direct comparison with the previous constant flight speed law.

Firstly, the selection of a sweep over different values of C_L is required, so as to provide the data needed by the additional dimension of inputs which corresponds to the flight law itself. Values of cruise C_L for RPA are not as common in the literature as flight speed values, so no immediate references values for the RQ-2 Pioneer have been found. Therefore, in this case, the sweep interval has been selected to approximately match the values of C_L which were seen in the case of the constant V flight law, with this interval being 0.35 - 1.35. It is noted that this last value, being so close to stall, would most possibly not be practicable for operation. However, as in the analysis of the previous flight law, a wide interval has been selected so as to better study the trends and effects that the C_L selection has in the remainder of the variables. In any case, in the research of (17), it can be seen that cruise C_L values of 1.1 are reasonable for RPA long endurance missions. The behaviour of the full

PL-R and PL-E diagrams when modifying the value of lift coefficient employed along the mission segment is shown in Figure 9-20.

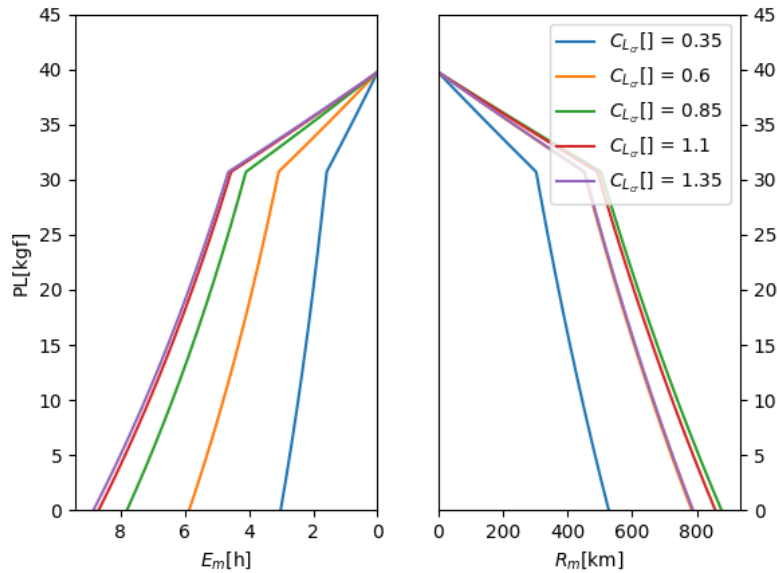


Figure 9-20. Variation of PL-R and PL-E envelopes for different lift coefficients for the RQ-2 Pioneer RPA case study.

Albeit the contour of the envelopes once again shows a remarkable change depending on the selected value of C_L , there are key differences in the behaviour which is observed here when compared to the constant airspeed flight law. One of the main dissimilarities is that the diagrams in this case seem to exhibit a uniform increase or decrease with C_L along their interval of values of PL , whereas in the flight speed case, the effect of changing the flight law variable sometimes resulted in the different envelopes crossing each other. It was proposed that the aforementioned behaviour in the constant V flight law was due to the differences through the same diagram on the values of average C_L along the flight. In this case, the lift coefficient is the same for all diagram points corresponding to the same value of C_L , as it does not change along the flight, which can be considered to substantiate this different behaviour.

With respect to the shape of the contour itself, it overall shows a slight curvature here through all of the values of the flight law variable when compared to the previous scenario of constant V , where depending on the value, some diagram contours were more noticeably curved, whereas others practically corresponded to straight lines. It is considered that this is due to the differences in the equations governing each of the flight laws, as it was seen for a simplified case within 9.2. These changes in fundamental behaviour highlight the advantage of having a performance tool which can allow to evaluate both kinds of flight laws.

Moving on to the numerical values of the results themselves, here it is once again seen that the C_L which achieves the optimum performance is different in the case of range and in endurance, with the same reasoning to the one expounded beforehand applying here. It is noted that, as the C_L is set by the flight law in this case, and considering that the altitude is also constant, the flight speed must change along each flight to maintain the vertical equilibrium of forces. Thereby, it can be worth studying the magnitude of the changes in V experienced by the aircraft along its flight due to the use of this constant C_L flight law, as this could have an impact not only on ATM and navigation considerations, but also in the accomplishment of the mission itself. This is seen in Figure 9-21 for two different C_L values.

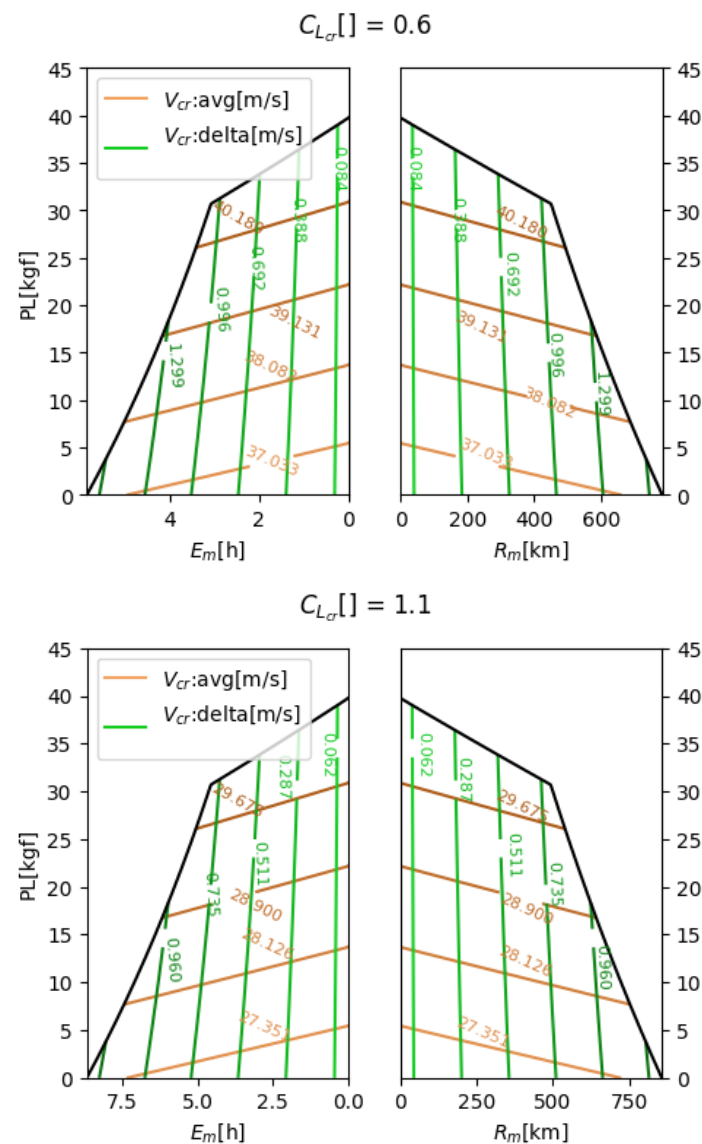


Figure 9-21. Iso-curves for both average V value along the mission stage and its delta for different flight C_L values corresponding to the RQ-2 Pioneer RPA case study.

For the diagram corresponding to the lower C_L , the flight speed average values are higher in general, which is consistent with the vertical equilibrium force equation. Larger values of flight speed are required towards the top of the diagram, since the weight of the aircraft also grows through the increase in PL . The variations of C_L along the flight are larger for the case of lower C_L , but in any case they are low when compared to their average values. Therefore, in this case it can be expected that the variation in flight speed which is required along the mission segment to maintain the equilibrium of forces will not cause issues for the development of the mission.

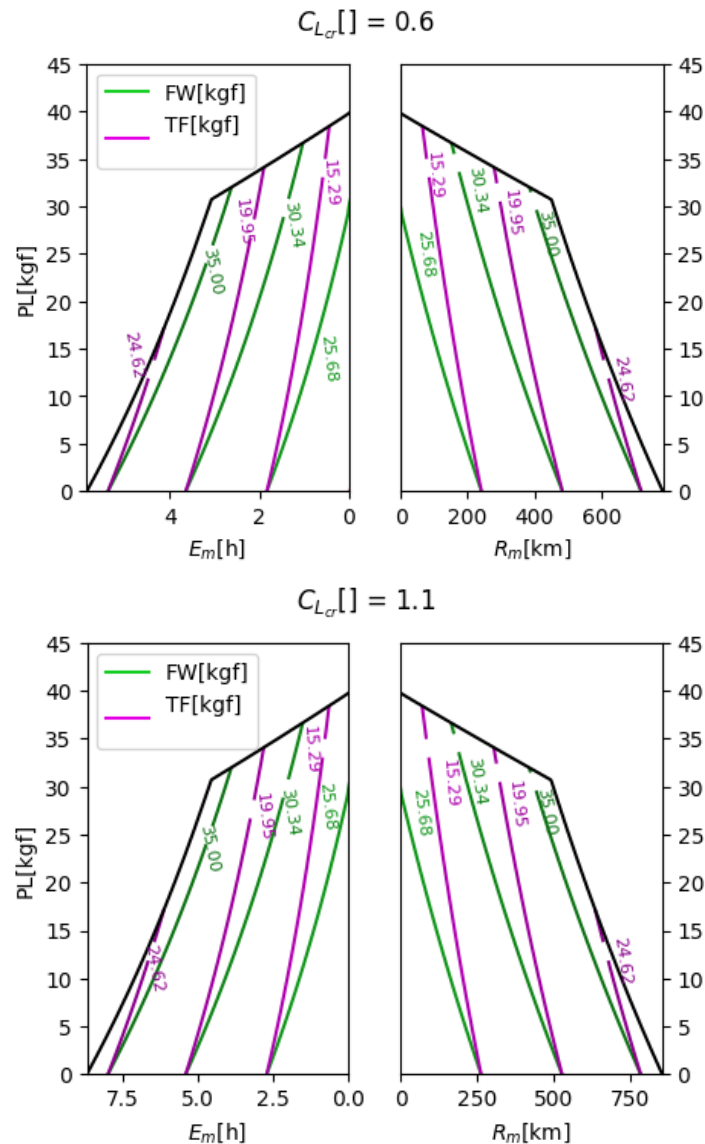


Figure 9-22. Iso-curves for TF and FW for the Pioneer at two different lift coefficient values.

In a similar vein to the previous study on the constant V flight law, the iso-curves corresponding to the integral variables of TF and FW are also analysed, as shown in Figure 9-22. The behaviour is mostly similar to the one seen in 9.4.1, however in this case, owing to the more uniform curvature shown by the diagram through the different values of C_L ,

this also influences the iso-curves, in contrast to the constant V scenario where depending on the flight law variable, some diagrams showed a lower curvature of these loci of points than others.

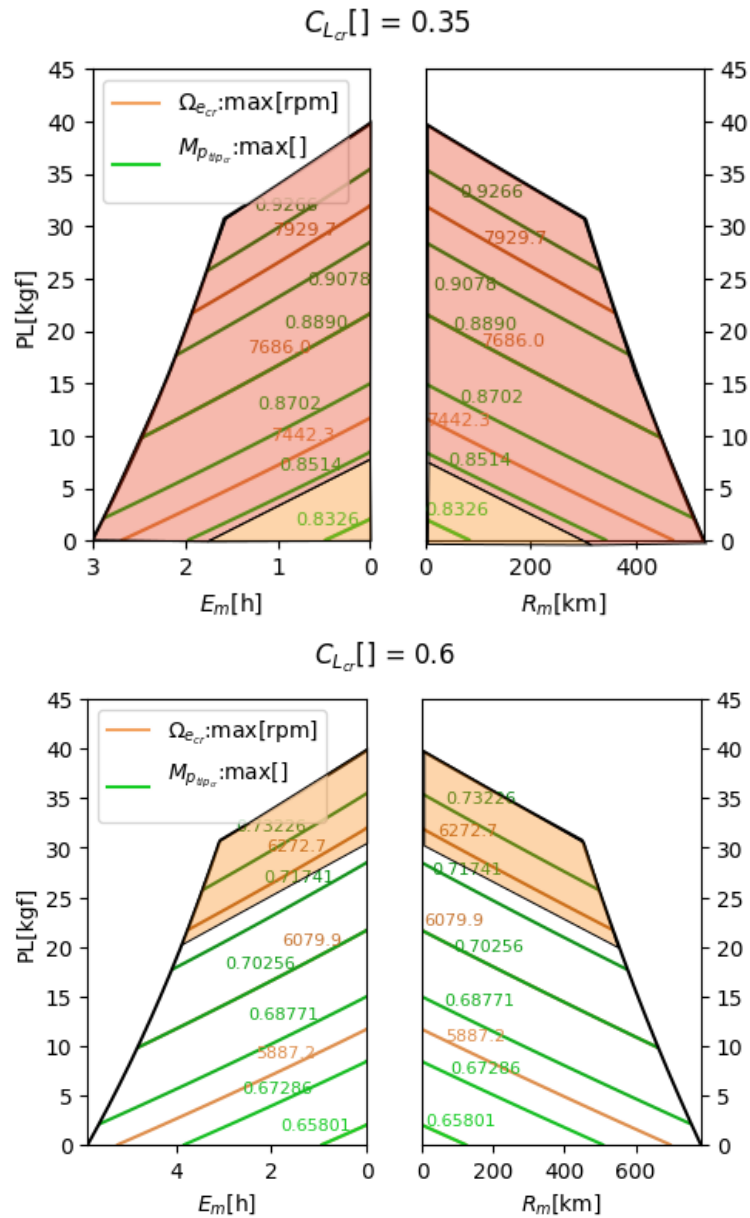


Figure 9-23. Iso-curves for maximum Ω_E and M_{ptip} along the mission stage, represented for different lift coefficients corresponding to the RQ-2 Pioneer RPA case study. The region where noise issues might appear due to the propeller angular velocity is highlighted in orange, and that where transonic effects occur is marked in red.

Finally, and considering the potential issues with Ω_E and M_{ptip} as seen in 9.4.1, the iso-curves corresponding to the maximum values that they take along each flight are also represented for this scenario in Figure 9-23. Here, it is seen that higher lift coefficients result in lower average engine revolutions, which matches the findings from 9.4.1, since growing values of C_L are associated to lower speeds, and it was seen beforehand that

engine revolutions decrease when V lowers. However, as C_L decreases, there is a sharp rise in both Ω_E and M_{ptip} , and even through the same diagram, as it can be seen for the case of $C_L = 0.35$, the behaviour changes remarkably, with even the maximum engine revolutions being surpassed in the points at the top of the diagram in this case. The same criteria of noise and transonic effects regions that was introduced in 9.4.1 has been employed in these images.

Overall, it can be seen that the performance of the aircraft showcases noteworthy dissimilarities when considering both flight laws, with some notable cases being the different shapes of the diagram contours and also the ways in which different restrictions behave in each case. This emphasises the significance of considering both options, so as to enhance the number of options available when analysing the performance of the RPA and planning its missions. Further aspects aside from those which are purely related to performance should also be considered at that point, such as the way in which the information gathering process by the payload might be affected by the distinct flight laws. It is also seen that obtaining the iso-curves has been key not only to describe in a more comprehensive manner the performance characteristics of the aircraft, but also to detect the mission regions where certain flight restrictions apply, which would not be detected in other cases by employing simplified models. With the above, it can be considered that the new performance analysis approach proposed in this chapter provides satisfactory results with respect to allowing to analyse an expansive mission space and offering a remarkable volume of information to the designer about the RPA of interest.

9.5. Performance estimation results and discussion: sensitivity analyses

Aside from the results of the previous section, and following with the capabilities of the performance analysis model which was developed in 9.3.1, remarkable insights can be obtained by performing sensitivity analyses on the aircraft which is being analysed. This capability was described at the end of 9.3.1, where it was expounded that it consists in varying a certain parameter of the aircraft model instead of the flight law variable. These parameters include aspects related to design, such as the *OEM* and the coefficients of the drag polar; and also features linked to the mission planning, such as the fuel reserve fraction α . It was already seen beforehand in the case study of the previous section, particularly in Figure 9-13, that these type of parameters can have a very significant impact in the mission space through their influence in the boundaries of the diagram.

Thus, a case study of the influence that these design and mission parameters can have in the mission space of a given aircraft is conducted in this section. Whereas the information provided by the flight law analysis was noteworthy mainly from a mission analysis perspective, the insights provided by these sensitivity studies can be considered valuable from both a perspective of design and of mission planning, as it will be seen afterwards through the specific analysis cases. Before moving forward, it is key to highlight that these

sensitivity analyses are considered within the scope of the conceptual design stage. In more advanced stages, complex interactions between the variables to be studied here can be evaluated with more accuracy through higher fidelity approaches. However, the interest of conducting this study here considering each variable on its own is to evaluate the impact on the mission stage of potential design improvements or operational decisions. Thus, a more comprehensive modeling on interaction effects among various parameters is considered outside the scope of the analyses carried out here.

The RQ-2 Pioneer RPA will once again be the aircraft of study in the sensitivity analyses presented here. In this case, the data of Table 9-3 shall be modified depending on the sensitivity study which is being conducted at each point. As the flight law is kept at a constant value in this case, the reference case selected shall be the constant flight speed case with $V = 35$ m/s, which showed satisfactory characteristics overall in the performance evaluation carried out beforehand.

Firstly, and following on the findings at the start of 9.4.1 with respect to the significant influence of the RF on the PL-R and PL-E diagrams, the case of varying α shall be analysed. This case is focused on potential variations in mission planning, which might involve augmenting or lowering the fraction of RF depending on various considerations. For instance, if the aircraft is equipped with a parachute, or alternative recovery spots are available through the mission area, it might be possible to lower α without compromising the safety of the operation. In contrast, should the operation be carried out in complex terrain or in a location with no recovery spots readily available close to the mission trajectory, it could be necessary to increment the reserve fuel fraction.

The results from this sensitivity analysis are represented in Figure 9-24. As in the beginning of 9.4.1, it can be seen that the impact of this operational parameter on the mission space is outstanding. For instance, with respect to the nominal case of $\alpha = 7$ %, the use of a 1 % fuel fraction results in an increase of maximum endurance of up to 67 %. The significant influence of the RF as seen here is also consistent with the marked difference between FW and TF as studied beforehand in Figure 9-16.

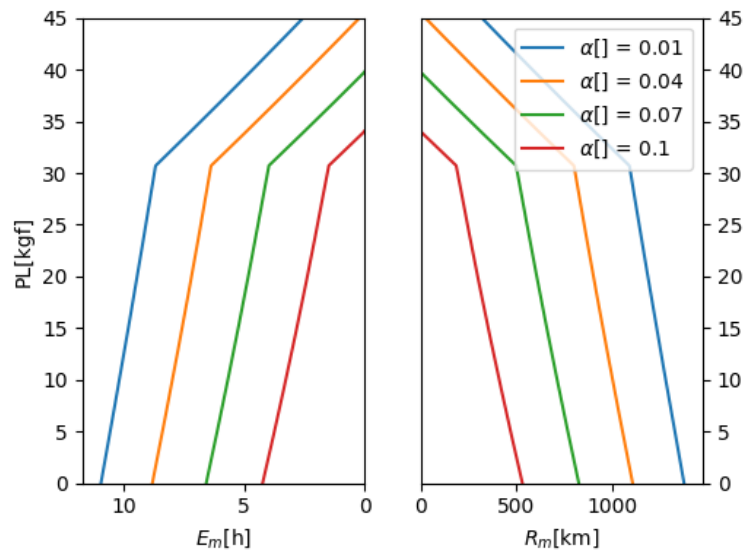


Figure 9-24. Sensitivity analysis of the PL-R and PL-E envelopes of the RQ-2 Pioneer upon changing the reserve fuel percentage.

It can be seen that decreasing the reserve fuel fraction can be an inviting alternative to improve the performance of the RPA. However, due to the relationship of this parameter with safety aspects, an evaluation depending on the mission and on each particular operational scenario should be conducted beforehand. The reduction of the fuel mass fraction could be better suited for small RPA, particularly those that can be equipped with a parachute, as their relatively lower impact energy, and their recovery versatility mitigate the potential risks of the RPA running out of fuel.

The following sensitivity study shall focus on the *OEW*. Variations in *OEW*, and more specifically, in the *OEW/MTOW* ratio, can be caused due to different reasons. Increases in this fraction can occur due to the need to include additional systems and equipment aboard the aircraft, which might not be related to the payload itself, but could be needed to support and guarantee the success of some particular operations. Additionally, the study of the increase in this fraction at the design stage could be used to model a phenomenon known as weight growth, which is related to the fact that, due to the inaccuracies of weight estimation models used through the design stage, it is usual that the manufactured aircraft has a larger weight than originally expected. This type of occurrence is not only seen in manned aeroplanes (9), but also in RPA (105). On the other hand, decreases in this weight fraction can represent improvements in technology and structural design. The results of studying a 10 % relative increase and decrease from the original value of *OEW*, while keeping the same *MTOW*, are illustrated in Figure 9-25.

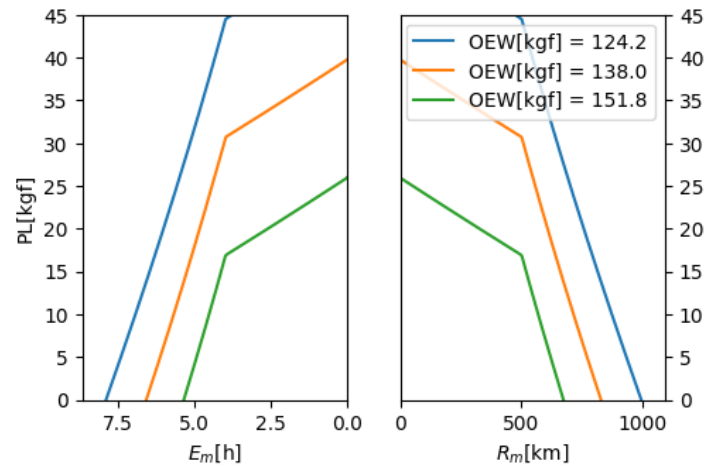


Figure 9-25. Sensitivity analysis of the PL-R and PL-E envelopes of the RQ-2 Pioneer upon changing the OEW.

It can be seen that the $OEW/MTOW$ fraction has an even more remarkable influence in the RPA performance than the reserve fuel fraction when considering the same percentage variation in the parameter which is being changed. Here, there is a significant effect in terms of range and endurance, but even more so with respect to the payload that the aircraft can carry. As a matter of fact, a 10 % decrease in the empty weight fraction, without changing the value of α with respect to the nominal case, enables to carry the MPL to the operation point with a $R_{ineg} = 90$ km, which was not possible beforehand. This highlights the relevance of structural and airframe systems optimisation in terms of performance, which is a matter that can be taken into account in further stages of design, based on the findings presented here.

Another relevant possible variation in the area of design aspects would be changes in the drag polar C_{D0} coefficient. The practical significances of this, in the particular case of RPA, can be varied. As mentioned beforehand through this chapter when discussing the topic of the drag polar, it was commented that elements such as payload bubbles, fixed landing gears, and additional protuberances and excrescences represent a significant portion of the lift-independent drag of typical RPA. Therefore, the changes in C_{D0} to be analysed here can represent, in the case of drag growth, aspects such as a change to a less streamlined payload or the addition of an antenna required for a certain operation. On the contrary, improvements to C_{D0} can correspond to the removal of the fixed landing gear, the use of a retractable one, or the addition of improved fairings for the payload and other external elements. The results are shown in Figure 9-26 for relative changes of 20 % in the original value of C_{D0} . This value was selected in this case so as to enable a better visualisation of the results.

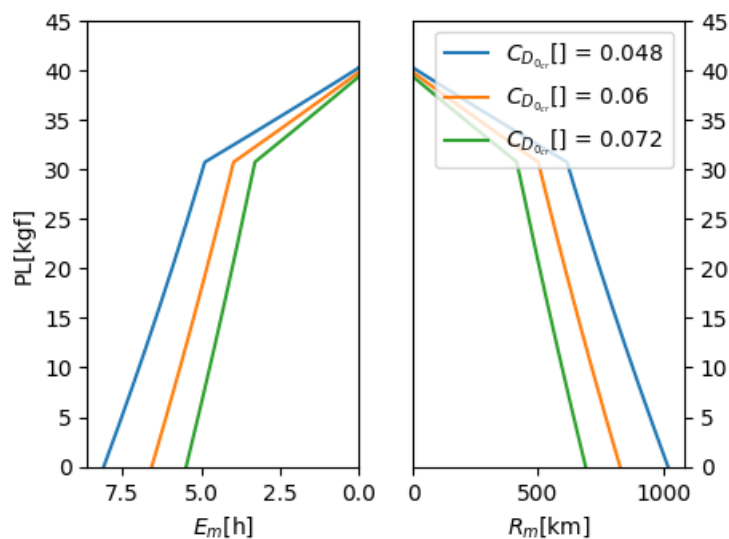


Figure 9-26. Sensitivity analysis of the PL-R and PL-E envelopes of the RQ-2 Pioneer upon changing the value of C_{D0} .

The way in which this type of change impacts the PL-R and PL-E diagram is significantly different to that of the OEW. Here, one of the advantages can be seen of evaluating the sensitivity of the full PL-R and PL-E diagrams, which is one of the original aspects provided by the proposed analysis methodology. This is that, of the three effects studied until now, each of them influence the geometry of the diagram boundaries in different ways. This information would not be available if only the sensitivity of a single mission, for instance the design operation, would have been analysed.

The results show that there is also a significant variation in performance, which even accelerates as the C_{D0} improves, since the difference between the upper value and the baseline one is larger than the distance between the baseline and the lower value. Therefore, and particularly since RPA tend to have values of C_{D0} which are remarkably high in comparison with other aircraft, the possibility of improving the aircraft's performance through a reduction in C_{D0} appears to be a worthwhile avenue of investigation. However, in relative terms, the influence is lower than that of OEW, as in that case variations of 10 % were considered (so as to avoid exaggerated changes in the diagram which may not represent feasible scenarios), whereas here the changes have been of 20 %, and both cases showcase a similar increase in maximum range and endurance. It is noted that the impact of changes in C_{D0} in the upper part of the diagram is almost negligible, whereas this was the region that saw the greatest impact in the case of OEW. A conclusion that can be drawn from this is that, depending on the type of capabilities of the RPA that are sought to be enhanced, different design modification approaches might be more efficient.

Finally, the variation of the whole diagram upon changing the quadratic coefficient of the drag polar, designated as either C_{D2} or k , is studied in Figure 9-27, where relative changes

of 20 % have also been considered. The variations follow approximately the same pattern as those of C_{D0} , albeit in this case are not as large. In spite of this, the positive effect on performance that can result from improvements in the effects that are represented by this coefficient can be leveraged on their own or in combination with other avenues of performance improvement as seen through this section. In this case, relating the variations of this parameter with more tangible aspects is not as immediate, as in three-term drag polars the C_{D2} coefficient includes a multitude of effects. From a broad perspective, improvements in this aspect can be due to reductions in wing vortex drag, which may be achieved for instance through an increase in the AR or the addition of winglets; and also through the decrease of fuselage lift-dependent drag, which can be achieved through a reduction of vortex drag or the viscous lift-dependent component, with the first component being mostly connected to fuselage volume and the second to planform area (7). In this way, the use of tail booms rather than extending the fuselage up to the tail unit could be investigated, if this is allowed by other design considerations.

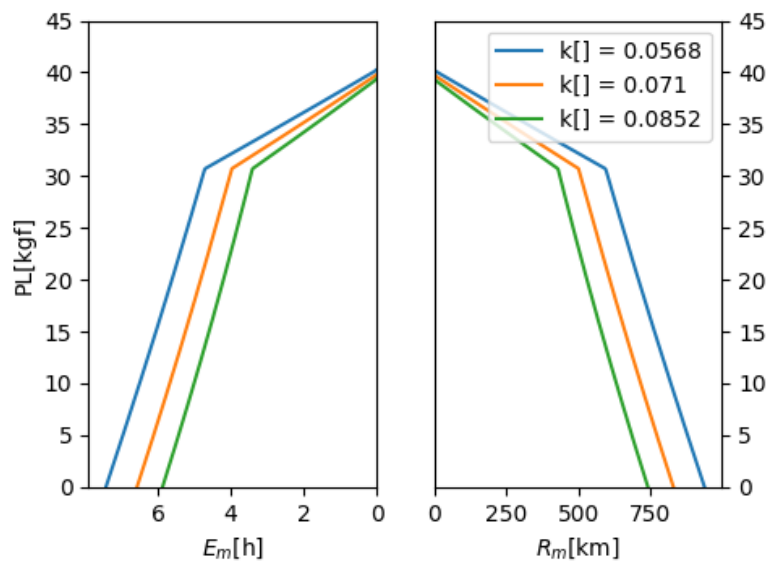


Figure 9-27. Sensitivity analysis of the PL-R and PL-E envelopes of the RQ-2 Pioneer upon changing the value of the drag polar coefficient $k \equiv C_{D2}$.

The sensitivity analyses which have been enabled by the rapid performance estimation approach that is proposed in this chapter have revealed significant insights related to the way in which distinct parameters affect the mission space represented by the PL-R and PL-E diagrams. As it has been seen, the ways in which each studied parameter influences the geometry of the diagram's boundaries is remarkably different in each case. Furthermore, the fact that there is a strong impact on the diagram as a whole highlights the relevance of conducting this study on the whole operational space, as key information could be missed if the sensitivity of only particular missions is analysed. This constitutes an improvement over previous approaches seen in design methodologies up to now,

since the assessment of the sensitivity of the full PL-R and PL-E diagrams has not been found in previous works when conducting the state-of-the-art analysis of this chapter. Thus, this approach would constitute one of the novel contributions of the thesis.

Finally, it is highlighted that, while evaluating the sensitivity of the mission space overall might not be as critical for manned transport aircraft, the significance of this in RPA is noteworthy. This is because these aircraft present an outstanding diversity of mission with remarkably different characteristics, so analysing which areas of the operation space might be more affected by certain parameters can be considered to constitute a worthwhile avenue of analysis, particularly considering the peculiarities of these aircraft.

9.6. Multi-role initial sizing results and discussion

This section covers the final group of case studies of this chapter. In this case, moving on to the multi-role design methodology, the purpose is to test this novel approach that has been expounded in 9.3.2 to two different cases. The main objective is not only to validate the design process, but also to assess how its capabilities can provide significant information to the designer when tackling the challenge of performing the initial sizing of a multi-role RPA.

The first case study, which is conducted in subsection 9.6.1, follows a similar philosophy to the ones that were carried out in chapter 7. The underlying idea is to set as the inputs of the methodology the initial specifications of a RPA whose mass and geometry characteristics are also known, so as to then compare the results of the sizing methodology with those of the existing RPA. Then, subsection 9.6.2 conducts an application case of a novel RPA with initial specifications representing a variety of missions, seeking to leverage the flexibility of the methodology. The results of the design process are then evaluated and discussed.

9.6.1. Validation case: Seeker 2E

This case study seeks to assess the accuracy of the multi-role sizing methodology when applied to the case of an existing RPA which has not been included in the database nor evaluated beforehand in previous application scenarios of this thesis. Albeit the procedures which have been used in the development process of the RPA to be studied here are not known, and other possible design considerations could apply, the purpose is to evaluate whether, from the viewpoint of conceptual design approaches, the proposed multi-role sizing methodology can produce as an output an aircraft which is similar, within the margin of error of conceptual design, to the existing one. A good agreement between the results of the methodology and the real data would serve to validate that the approach can be used to produce RPA concepts which share similar characteristics to those of the deployed aircraft.

The RPAS that will be the focus of this validation case is the **Seeker 2E**. This is one of the very few aircraft in the database compiled through the work of this thesis for which the payload and endurance characteristics for two distinct points of the PL-E diagram are known (37). Albeit the remaining parameters which are needed by the design methodology (V or C_L , h , and R_{ineg}) have not been found for these particular missions, typical values of the first two pertaining to the operation of this aircraft are known (37; 389; 390), so they can be approximated as the values corresponding to the two operations given in the literature. In the case of R_{ineg} , and considering that the two given missions seem to represent maximum performances of the aircraft (37; 389; 390), it has been assumed to be zero, since this would be the operating case that would allow the RPA to achieve its maximum endurance in each of the cases represented by the combination of the other four parameters. This is also the reason for a reduced value of α being assumed for this case study, because as it was seen in the sensitivity analyses of the previous section, the impact of carrying additional reserve fuel on the performance is remarkable. In this case, if the manufacturer is listing maximum performances, the most possible scenario is that they have been calculated with the most advantageous operating parameters as possible.

Before moving forward, it is key to highlight that it is not possible to know, from the information which has been gathered, if these two missions are in fact design points used in the development process of the RPAS. Therefore, this should be considered as a potential source of error, aside from the uncertainties with respect to three of the five inputs of the design methodology as commented beforehand.

With the information commented beforehand, and completing some of the required inputs of the methodology with typical values of similar aircraft within the state-of-the-art, the set of inputs is set as seen in Table 9-4.

Table 9-4. Summary of inputs for the multi-role design methodology applied to the case study corresponding to the Seeker 2E. Information mainly obtained from (37; 389; 390).

Mission specifications			Other design process inputs	
Variable	Mission 1 (M1)	Mission 2 (M2)	Variable	Value
PL	50 kg	40 kg	α	0.01
E	12 h	15 h	η_{LG}	0.305
V	36 m/s	36 m/s	η_{PL}	0.193
h	1000 m	1000 m	C_{pm}	$1.27e^{-7} \text{ s}^2/\text{m}^2$
R_{ineg}	0 km	0 km	Ω_{Emax}	8000 rpm

On the other hand, albeit a complete geometric definition of the Seeker 2E including its tail surfaces, fuselage, and boom dimensions has not been found in the mentioned references. However, the data which are available with respect to its main design mass variables and overall dimensions can be used to compare the outputs of the design methodology applied here so as to obtain the relative errors. Finally, the geometric sizing

process to be used within this workflow has been selected to be the one based on factor analysis, leveraging the fact that this RPA has an H-tail layout.

The results from the case study, including the comparison with the values of the original aircraft, are provided in Table 9-5.

Overall, and taking into account the uncertainties of the data gathering process and the array of inputs given to the methodology, the results can be considered satisfactory. Albeit there are a couple of variables showing larger errors than the rest, none of the predicted characteristics surpass an error of 20%. Some comments on each of the particular result groups are made below.

Table 9-5: results from the Seeker 2E validation case.

Variable	Units	Real value (Seeker 2E)	Value of output RPA	Relative error
<i>MTOM</i>	[kg]	240	278	15.8 %
<i>OEM</i>	[kg]	150	166	10.7 %
<i>MPL</i>	[kg]	50	50	0 %
<i>MFM</i>	[kg]	61	71.6	17.4 %
<i>S_w</i>	[m ²]	4.43	3.90	-12 %
<i>b_w</i>	[m]	7	6.27	-10.4 %
<i>AR</i>	[-]	11	10.1	-8.2 %
<i>l_f</i>	[m]	3.09	3.05	-1.3 %

Firstly, with respect to *MPL*, it is noted that the result is identical to the original aircraft precisely because the value of *PL* given for M1 corresponds to a mission carrying the *MPL* of the aircraft. As commented in 9.3.2, the iso-curves of *PL* are horizontal lines which do not require performance computation, so from a practical standpoint, the value of *MPL* of the RPAs designed with this approach corresponds to the highest among the *PL_i* values of the different missions, albeit a margin can be added to absorb uncertainties in the model.

The mass variables are the ones where the largest errors can be found, both in *MTOM* and in *MFM*. This is understandable, as they come from the mass estimation approach of the sizing methodology, and albeit this step is based to a great degree on a physical-mathematical model of integral performance, it is also required to use the multiple regression shown in Figure 9-11. Albeit this empirical relationship shows satisfactory statistical metrics, it constitutes another source of uncertainty in the model, and as it was seen at that point, the combination of payload-dominated and performance-dominated vehicles in the same model could result in additional scatter.

Moving on to the geometric sizing results, the errors for the corresponding variables fall in line with the outputs of the case studies conducted beforehand in chapter 7, and they are overall satisfactory. It is considered at this point that this initial sizing approach, which is based on various iteration loops, presents a high degree of coupling among all of the variables. Therefore, certain interactions could arise that might affect the trends in the

errors seen in the results above. It was already commented in chapter 7 that one future avenue of research would be to scrutinise more accurately the ways in which the errors interact with one another. This would be more complex in this methodology, as there is a numerical performance resolution step in the workflow, aside from an additional correlation which is involved in this internal loop, as seen beforehand in Figure 9-12.

Therefore, albeit future investigations on the ways in which the errors interact could be conducted, the current results from the methodology can be considered reasonable for the conceptual design stage. In any case, future design stages would consider more factors from a higher fidelity perspective, with the final aircraft being a result of more accurate methodologies following an optimisation workflow. Therefore, it could be considered that these errors can be mitigated in subsequent design steps in the overall process, and that the main significance of this methodology is to provide an initial estimate of the aircraft concept which already complies with all the envisioned operations and that can be then refined in future phases.

9.6.2. Application case

Once the sizing procedure based on integral performance has been validated through the previous case application, here, a more complex multi-role aircraft, now not directly corresponding to any previously existing one, is tackled for its design.

As seen in the previous case, the full possibility of variations among the specifications of the different missions was not leveraged at that point, since only two dimensions were varied between the first and second operation, as no further data was available. In this case, since the application scenario is not based on a previously existing aircraft, a higher degree of variability can be introduced in the requirements. Thus, one of the main objectives of this application case is to leverage to a higher extent the possibilities of the design methodology presented in 9.3.2.

The sizing process to be addressed here shall be one of a multi-role aircraft envisioned to tackle three different design missions with remarkably distinct requirements. The sources consulted to propose these missions have been (1; 6; 27; 418):

- 1) **M1:** the first operation has been defined so that it represents a payload delivery mission at a short range, but carrying a significant mass when compared to the others. As this flight is from point to point, no ingress-egress segments would be required.
- 2) **M2:** the second mission is one with a slightly lower payload, but as a counterpoint, there is a much more demanding range requirement. Here, a positioning flight is considered, as the need of a flight to the point where the mission is conducted has been assumed. Since this operation is defined in terms of range, and considering the long distance to be covered, it can be considered to fall within the likes of river monitoring or similar earth science endeavours.

- 3) **M3:** finally, the third mission has a very light payload, but would represent a high endurance surveillance purpose, as the aircraft must stay over the target for 16 hours. Furthermore, the flight law here is defined in terms of C_L selecting a high value, so as to enhance the performance of the aircraft and aid in the accomplishment of this demanding mission.

These missions have also been selected seeking to generate conflicting requirements in the design process, so as to also assess the capabilities of the methodology to manage these scenarios, and the results that it produces as an asset for the designer to make decisions regarding this kind of design challenges.

With this, the set of inputs to be provided to the multi-role design methodology can be summarised in Table 9-6. It is seen that corrections for LG and payload drag have been applied to account for the fact that the resulting aircraft is expected to be of a size that would require take-off and landing in runways, but still not reaching values of $MTOM$ where the use of retractable landing gears is common. This can be revised in view of the outputs of the design process. As in the previous case, the selected layout is H-tail and the sizing approach shall be the one based on factor analysis.

Table 9-6. Summary of inputs for the multi-role design methodology conducted for the RPA application case considering three design missions.

Mission specifications				Other design process inputs	
Variable	Mission 1 (M1)	Mission 2 (M2)	Mission 3 (M3)	Variable	Value
PL	100 kg	85 kg	30 kg	α	0.07
R or E	100 km	1000 km	16 h	η_{LG}	0.19
V or C_L	40 m/s	35 m/s	0.9	η_{PL}	0.25
h	1500 m	1000 m	2000 m	C_{pm}	$8.8e^{-8} \text{ s}^2/\text{m}^2$
R_{ineg}	0 km	50 km	160 km	Ω_{Emax}	8000 rpm

As an additional dimension to this application case, the sizing process shall also be conducted for each of the RPA which would result from only considering each of the individual design missions, as well as the dual mission RPA resulting from combining the specifications of each pair of missions. This results in a total of seven design cases: three for single-role aircraft, three for dual-role aircraft, and one for a multi-role RPA covering all three missions. The results from this set of cases are summarised in Table 9-7.

Table 9-7: results from the application case of the multi-role methodology. The number combinations represent the joint missions that have been considered in each design case.

Variable	Units	M1	M2	M3	M12	M13	M23	M123
<i>MTOM</i>	[kg]	342	377	230	413	490	449	499
<i>OEW</i>	[kg]	197	216	129	243	310	266	310
<i>MPL</i>	[kg]	102	87	31	102	102	87	102
<i>MF_W</i>	[kg]	43	72	63	78	132	113	130
<i>S_w</i>	[m ²]	4.5	4.9	3.4	5.2	6.0	5.6	6.0
<i>b_w</i>	[m]	6.9	7.3	5.8	7.7	8.4	8.0	8.51
<i>AR</i>	[-]	10.6	10.9	9.7	11.2	11.9	11.5	12.0
<i>L_h</i>	[m]	2.41	2.50	2.11	2.6	2.80	2.69	2.8
<i>S_h</i>	[m ²]	0.83	0.89	0.65	0.95	1.07	11.5	1.1
<i>S_v</i>	[m ²]	0.61	0.65	0.49	0.68	0.76	0.72	0.77
<i>C_{D0}</i>	[-]	0.035	0.035	0.036	0.035	0.035	0.035	0.035
<i>C_{D1}</i>	[-]	-0.011	-0.011	-0.011	-0.011	-0.011	-0.011	-0.011
<i>C_{D2}</i>	[-]	0.050	0.049	0.053	0.048	0.046	0.047	0.046

There are many insights which can be extracted from the above results, with the focus in the following discussion being focused on some of the main aspects commented through this chapter:

- **Overall results:** it is seen that the multi-role RPA is remarkably distinct from the single-role aircraft sized for each of its individual missions, and it is even notably different from most of the ones accomplishing two missions. This highlights the noteworthy impact that the design missions have in the resulting aircraft, which was already seen in previous works in the state-of-the-art of manned aeroplane design. The RPA which seek to accomplish more missions have much higher values of design mass variables, which in turn drive the geometry increase, so that they also larger.
- **Mass estimation:** since this step determines the values that will be used in the geometric sizing process, it has a significant influence in the resulting design.
 - From the three single-role aircraft, it is seen that the one with highest MTOM and OEM is the one that has to comply with a combined requirement of a payload with a significant mass that has to be carried along a noticeable distance. Albeit none of these individual requirements are as demanding as the ones of M1 or M3, their combination produces an interaction effect which results in a larger MTOM being needed. This can be explained in view of the coefficients of the multiple regression shown in Figure 9-11, and it connects with the discussion developed there with respect to the combination of simultaneous payload and performance requirements.

- When moving on to the RPA that comply with two missions, it is seen that the worst scenario is the one that combines the very demanding MPL requirement of the first mission with the endurance specification of the third operation. To cover these two points, and attending to the underlying idea of Figure 9-10, the PL-R and PL-E diagrams have to cover a substantial overall area. As seen in previous aircraft design works (412; 415; 416), and as commented beforehand in this chapter, there is a trade-off between mission flexibility and efficiency. In this case, the high surface area enclosed by the diagram so that it can cover those design missions located at different extremes results in a larger aircraft. In fact, the difference between M13 and M123 is small most possibly because in the case of M13, the resulting diagram nearly also envelops the point corresponding to the second mission, requiring only a small increment to arrive at the multi-role RPA. In contrast, since the points of M1 and M2, and those of M2 and M3, are not that far apart, the effect is not as significant.
- Albeit this is not seen in the table, it is noted that for the M123 RPA, each of the missions drives a different design mass, with the first one determining *MPL*, the second one *MTOM*, and the third one *MFM*.
- Finally, it is interesting to note that the *OEM/MTOM* fraction remains in relatively similar values among the different aircraft. This may be due to the use of the multiple regression, as the empty weight fraction of the resulting aircraft might be influenced by that of those RPA included in the empirical relationship.
- **Geometry sizing:** since this step mainly depends on the value of *MTOM* obtained in the previous one, most of the results can be explained through the discussion given above. Overall, it is seen that the geometric dimensions of the different components are consistent among them and with the mass values, and checking with aircraft with similar values of *MTOM* from the state-of-the-art, no uncharacteristic results are detected.
- **Drag polar:** the variations in the drag polar are generally low. This may be expected as all of the aircraft have the same layout, with the differences happening mostly due to the changes in size of the components. The largest changes are seen in C_{D2} , with variations of up to 15 %. These dissimilar results can be expected to be mostly due to the variations in the AR modifying the contribution of the wing vortex drag.

Overall, it can be seen that considering distinct design missions at the design stage results in noticeably different resulting aircraft. This highlights the relevance of developing such a multi-role approach that can be used in the conceptual design stage. If these differing

specifications are not considered early on, the convergence of the design to an aircraft which can comply with all requirements might be hindered at later steps of the development process. In contrast, if the initial concept has been sized considering all of these requirements, this can be expected to aid future optimisation procedures and higher fidelity approaches to further refine and improve the design starting from a satisfactory baseline.

Finally, the ways in which this information can aid the designer to make decisions with respect to negotiating requirements is also worth highlighting. In this case, from the single-role RPA, it is seen that the most distinct final aircraft is the one corresponding to the long endurance mission, M3. When moving on to the RPA that accomplish two roles, the M12 one is that which shows less penalty with respect to the original two single-role designs, whereas the other two cases result in significant increments in mass. Moreover, cases M13 and M123 are remarkably close to each other, signifying that not much more effort is required to integrate mission 2 to the RPA if already the first and second ones are to be accomplished.

Considering the above, and within the context of requirements analysis and negotiating specifications, two main avenues could be explored by the designer:

- If the requirements only included M1 and M3 as necessary requirements, but the operational perspectives of M2 seemed promising, there is not much more penalty to the design to integrating M2, so it could also be considered at the design stage and could result in an operational advantage of the aircraft, while only adding 9 kg of MTOM.
- However, if among the three operations, the one which can be expected to see the most use is M3, it might not be advisable to combine this one with the others due to the efficiency penalty that the aircraft suffers. In this case, an option that could be put forward could be to design two distinct RPA: M3 and M12.

These kind of decisions are paramount within the aircraft project and they might potentially have a remarkable impact in the rest of the steps of the development process, as commented in 2.1.2. This is one of the reasons why the use of conceptual tools is key to aid the designer in identifying potential avenues of analysis and research before the project moves forwards and the layout of the aircraft is fixed, since this type of decisions cannot be feasibly made later on.

However, the above possibilities should be consider under the light of many more aspects which have not been included in the scope of the model, including RPA use and costs, among others. These constitute future avenues of work to improve the methodology developed here. In any case, at this point, it is seen that this sizing process provides a rapid and significant amount of information which can be used in the initial design steps to guide future decisions and efforts.

9.7. Summary and conclusions

The investigation conducted in this chapter has been motivated upon detecting certain gaps in the current state-of-the-art with respect to the development of analysis and synthesis approaches for multi-role RPA, which on the other hand, is one of the most outstanding characteristics of these aircraft. The development of new methodologies which can aid the designer in the initial steps of the process while accounting for these aspects may constitute an asset towards leveraging to a higher extent in the future the multi-role potential of RPA. Thus, and following OBJ.3.3 of this thesis, this chapter has sought to propose novel methodologies both for multi-mission performance analysis, and also for multi-role initial sizing of RPA. At this point, many of the previous lines of research addressed through the thesis converge to provide tools and criteria so as to enable the development of the approaches proposed here.

Before developing the analysis and design methodologies themselves, the ways in which it might be needed to adapt the models required for the integral performance study of RPA were assessed. With respect to previous works, it was proposed to use a three-term drag polar and lift-independent drag corrections taken from RPA data, to define a flexible flight profile that can represent most of the typical missions of RPA, and to develop of a quasi-stationary approach that can allow to gather a significant volume of information with respect to the behaviour of the RPA through its mission space. This model then enables to set up the multi-role initial sizing approach, which leverages the statistical relationships extracted beforehand in chapter 7.

With respect to the rapid performance estimation approach, one of its foremost characteristics is the possibility of summarising a large amount of data pertaining to the integral performance of the aircraft and presenting it through PL-R and PL-E diagrams. These envelopes are enriched with a set of iso-curves that allow to analyse the behaviour of the RPA within its flight envelope, and they summarise not only the information relative to each flight as a whole, but also the changes of key variables along each of the flights represented in the mission space. This provides the designer with a substantial array of information to evaluate the operational possibilities of the RPA, which can later on be used for design purposes. The most noteworthy insights that can be gathered through the use of this methodology would be:

- 1) The **exploration of an expansive mission space** covering many different possible RPA mission types, as the model allows to change the geometry of the flight profile, the flight law and the value of its defining variable, as well as other model parameters.
- 2) The possibility of **detecting areas of the mission space in which particular trends and hurdles appear**. For instance, the designer can readily identify the ways in which certain variables such as the lift coefficient or the TF vary along the diagram, and identify those regions which might be more beneficial. On the other

hand, this also allows to detect areas where the flight might not be feasible or show significant issues, such as points of the PL-R and PL-E diagrams where stall would occur at certain point of the flight, or where other variables also show limiting behaviours such as reaching the maximum engine angular velocity or Mach number at the propeller tips.

- 3) Through the use of the model to **perform sensitivity analyses**, the **most suitable avenues to introduce modifications that can expand the design mission space** can be identified. This is enabled due the information provided by these assessment on how different parameters affect the PL-R and PL-E envelopes. For instance, it was seen that an reduction of OEM has a noteworthy effect in the top portion of the diagram, enabling the possibility of carrying heavier payloads, whereas the drag polar coefficients mostly affected the range and endurance for low value of payload.

With respect to the multi-role initial sizing approach, it allows to arrive at a rapid design definition of an RPA which is aligned with the requirements of the conceptual development phase. This methodology considers five main parameters to define each mission, and different flight laws and mission requirements can also be included here, as these capabilities come from the analysis process developed beforehand. Furthermore, the validation case showed that this approach results in satisfactory outcomes with respect to state-of-the-art RPA. With this, the main assets that this methodology can provide to the designer would be the following:

- 1) The input flexibility allowed by this approach enables it to **design RPA that can accomplish missions with very distinct characteristics**. Since mission diversity is one of the foremost characteristics of these aircraft, it can be considered that the methodology developed here allows to cover a wide range of RPA applications, giving it a broad applicability range.
- 2) One of the foremost aspects of the methodology developed here is that it can **analyse the way in which each mission requirement impacts the resulting RPA**, even assessing the different aircraft that could result from considering each mission separately. This allows to analyse the design drivers, identifying the most demanding requirements.
- 3) The previous point enables the methodology to be used for requirements analysis and to **aid the designer in making certain decisions in view of the obtained results**. In some cases, specifications might be negotiated if a particular mission is resulting in a loss of efficiency of the RPA through its mission space. In contrast, if a promising operation which has not been included in the initial requirements is detected, and taking it into account does not hinder the resulting design in a significant margin, it can constitute an added operational advantage of the RPA. Therefore, the versatility and rapid calculation times of the methodology allow to

evaluate many possible scenarios to make design decisions with a broader scope, which is among the main objectives of the conceptual design stage.

- 4) Furthermore, as this method includes the statistical relationships of chapter 7, it can also leverage their capabilities, such as the **possibility of sizing different layouts**, which is a topic that will be explored in the following chapter.

There are additional avenues of research that could aid to expand the capabilities of the current methodologies. For instance, additional disciplines could be taken into account to expand the model, with cost analysis possibly enabling the designer to make more informed decisions such as the ones expounded in the application case of 9.6.2. Furthermore, additional flight laws could also be integrated in the model, and the mission flexibility could be expanded through the use of a combination of different mission segments with distinct characteristics, as it is currently done in certain design environments of manned aeroplanes (86; 99; 93).

At this point, it is considered that the purpose of OBJ.3.3 has been accomplished. The methodologies developed here are rapid tools that the designer can use to support the design process of multi-role RPA, not only enabling to obtain their sizing, but also providing information that can be key to make decisions with a broader scope and impact. Furthermore, the characteristics of the methodologies developed here also address some other points mentioned through the thesis, such as the need for a larger mission and method flexibility in computerised aircraft environments, or the possibility of developing RPA that can accomplish various missions through the use of a single air vehicle. The initial definition provided by these methodologies can then be used as the starting point of the calculations to be conducted within higher fidelity frameworks and approaches used in further design stages, while already providing a concept that verifies at this first stage the compliance with the design missions that are essential for its operation.

Within the scope of the thesis, there are two further points that can be integrated in the sizing approach proposed here, which are airworthiness requirements and point performance specifications, which were already addressed beforehand in chapter 8. The way in which these aspects can be integrated in the workflow proposed here shall be explored in the following chapter, which combines all contributions developed along part III of the thesis.

10. OVERALL CONCEPTUAL DESIGN METHOD RESULTS AND DISCUSSION

As brought forward in advance within chapter 6, the three distinct approaches that have been developed through this third part of the thesis have not only been created so that they can be useful in themselves, but they have also been devised anticipating their combined use to perform an overall initial sizing process of multi-role aircraft. Thus, this brief chapter conducts the process of integrating the procedures developed in the last three chapters, so as to then demonstrate their use as an ensemble sizing methodology through its application to a particular case of study.

As the background and validation scenarios for the distinct approaches have already been expounded in the preceding chapters, the focus of this chapter is on the specific aspects that arise from the combination of the procedures and on the results of the application case itself. Firstly, section 10.1 provides some brief considerations on the combined use of these approaches. Furthermore, the possibility of using these methods to aid in the overall RPA configuration selection is also explored. The ensemble of the approaches is then applied to a case of small RPA design in section 10.2, which leverages the aforementioned sizing and configuration selection capabilities.

10.1. Considerations for the combined use of the design approaches

Going back to the relationship discussed in section 2.3 between design approaches at a finer granularity with those that are more holistic and have a broad scope, it was seen that the ones of the first type usually serve as building blocks of those of the latter kind. This idea is similar to the integration to be commented in this chapter, as the purpose is to arrive at an overall initial sizing approach by using the methodologies developed in the previous chapters, which correspond to each of the topical areas of statistical approaches, design-airworthiness integration, and integral performance-based methods, respectively.

The topic of integration has been at the forefront of chapter 4 when studying the subject area of computerised environments. This notion was one of the main matters pertaining to the trend of modularity, interoperability, and integration, as developed in 4.4.2. It was seen in Figure 4-8 that these aspects are also a key enabler to enhance the capabilities related to other trends, including that of RPA design. Integration aspects can be considered from two different perspectives: that of the design methodologies themselves, and the one more related to the connection between software elements. These coincide with the two main areas of interest in the field of computerised environments which were used along the guiding thread of chapter 4. Even when outside the topic of design

packages, the consideration of integration aspects enables to improve the connection between design approaches of different kinds.

Here, the focus shall be on those aspects that are related to the design approaches themselves, as it is also according to the main scope of the thesis. All of the procedures used in the overall initial sizing approach presented in this chapter have been developed as part of the work of the thesis, which eases the task of integrating them. Furthermore, the type of methods that have been developed are rapid methodologies that do not require a large computation effort, so in this case the additional difficulties of integrating high-fidelity software that were commented in 4.4.2 would not be present.

Before moving forward, two different types of considerations with respect to design method integration are introduced here which will be key in this section:

- 1) **Integration in terms of workflow compatibility:** this relates to the perspective of the connection between building blocks in terms of the way in which the outputs of certain procedures link with the required inputs of others, so that the variables that are needed at each point are available from other previous tasks.
- 2) **Integration in terms of applicability consistence:** as mentioned through this thesis, ensuring that the design methods are applicable to the case which is being studied is essential to guarantee that the obtained results are believable. Applicability covers many aspects, from the hypotheses of the models, to the range in which an empirical regression can be used.

It was already discussed in section 2.3 that it is key to take into account integration aspects at the methods pertaining to the finer level of granularity so that their combined use to form approaches with a broader scope could be more streamlined. Some of these aspects have already been commented through the preceding chapters, and they will be complemented with additional considerations provided here. A summary of some of the integration aspects taken into account beforehand, which also accounted for the objective of using all design methodologies in a combined form which was laid out in chapter 6, would be the following:

- The two geometric sizing approaches based on statistical results proposed in chapter 7 need as a starting value the *MTOM* of the RPA. This variable is not an initial specification per se, but this aspect was covered by the mass estimation process based on integral performance developed in 9.3.2, with one of its main outputs being the value of *MTOM*, allowing to connect with the statistical approaches.
- Following with the DECEX procedure, as commented in chapter 8, it is not a design methodology itself, rather, it serves to populate design approaches with airworthiness requirements related to their scope. The procedure was developed with flexibility in mind so that it can adapt to different types of design methods,

extracting for each one the airworthiness constraints related to the key variables considered within the design approach scope. These additional regulatory considerations can then be integrated in the original design workflow, as it was done in the application cases of 8.5.

- As commented through chapter 4 and in particular within 4.4.2, it was seen that modularity is a characteristic that aids design method integration. Even if not necessarily from a computational standpoint, it can be considered that the three approaches developed in this part of the thesis have been developed following a modular perspective, as they each are focused on a particular area, and have well defined inputs and outputs that connect to each other.
- With respect to applicability aspects, where possible the methodologies have been developed to cover many potential analysis and design scenarios. This is the case of the DECEX procedure, which can adapt to various design workflows, and also of the performance analysis method developed in 9.3.1. In this latter case, as stated in the corresponding subsection, the configuration type of the RPA is not required to be explicitly stated, as the way in which this feature affects its performance is directly included through the drag polar model. In other cases, the scope of the methodology sets boundaries to its applicability, such as in the empirical regressions, which are applicable to RPA with reciprocating engines of four different configurations. However, it has been ensured that these aspects are consistent among the different approaches, as for instance, the performance analysis approach has been developed for reciprocating engine RPA, which are most commonplace in the database.

All of the above points aid in the process of combining the approaches to constitute an initial sizing approach that is to be commented in this chapter. At this point it should be noted, that, attending to the characteristics of the topical area of overall initial sizing as proposed in 2.2.3, the design method for multi-role RPA proposed in 9.3.2 could already be considered as an approach of this type. This reasons for this are that, starting from the initial requirements, which are the inputs of this design method, it enables to reach a conceptual geometric definition of the main elements of the RPA, including tail unit and fuselage. The outputs have a mathematical dependence with the specifications, as it was seen through the application case of 9.6.2, where different missions resulted in distinct RPA. Furthermore, the performance of the aircraft is checked to verify that it complies with the operational specifications. However, the methodology proposed in 9.4.2 has not still integrated airworthiness considerations, which will be done here through the DECEX methodology.

The following subsections cover the different integration aspects and other considerations which are emphasised in the process of using all three design approaches in a combined manner.

10.1.1. Combination of multi-role performance and statistical sizing approaches

It is noted that the combination of the integral performance-based method for multi-role RPA developed in chapter 9 with the statistical relationships that were extracted in chapter 7 has already been conducted in 9.3.2, as the geometric sizing process is an essential part of the overall multi-role sizing loop, as illustrated in Figure 9-9. Therefore, the integration between the methods of chapter 7 and 9 has already been accomplished. In this case, the combination has been relatively straightforward, as the outputs of the mass estimation step connect directly to the inputs required by the statistical geometric sizing process. Furthermore, the applicability of both approaches are compatible, since the focus of both is set on RPA with reciprocating engines.

The combination of these two different kinds of methods within the same workflow allows to leverage the advantages of each one when considering the characteristics of the other. For instance, the statistical process has certain degrees of freedom which can be set by the designer, particularly in the regression-based approach, but most of the workflow is relatively streamlined. In contrast, the inputs to the multi-role sizing approach as a whole, and thus to the mass estimation step, allow a higher degree of variability, leaving more room for changes according to the designer's criteria. The ensemble between each of these methods combines the use of empirical approaches with rapid physics-based ones, which is according to the usual type of conceptual design methodologies.

Up until now, in the cases of study of 9.6, only the factor analysis methodology has been demonstrated. In spite of the remarkable statistical results obtained by this method, it has only been possible to obtain a geometric sizing method of this kind for the H-tail layout. Albeit it is the most sizeable among the tail configurations as seen in the database overview provided within subsection 7.3.3, there are other layouts which have seen an extended use through the domain of existing RPA, including the conventional, T-tail and V-tail ones. These three layouts are considered along with the H-tail one in the regression-based methodology. Since one of the purposes of this chapter is also to propose a configuration selection approach, the geometric sizing approach based on regressions shall be employed in the case study to be developed in 10.2, as it is the one compatible with performing trade studies between different layouts.

10.1.2. Integration of airworthiness considerations in multi-role initial sizing approach

The area of RPAS regulations has been one of the main topics covered through the thesis, both in the study of the regulatory domain and its characteristics within chapter 3, as well as when developing the DECEX procedure in chapter 8. The introduction of airworthiness considerations in the initial sizing approach for RPA that is proposed here constitutes a remarkable prospect, particularly considering the comparative lack of previous works in this area as seen in the overall survey of chapter 2.

The main contribution of chapter 8 is that DECEX procedure itself, and in the application case conducted there, it was applied to the classic matching diagram process used to select the design point of the aircraft through the W_{to}/S_w and P_{to}/W_{to} . Albeit this diagram can include aspects related to the cruise flight such as required power and thrust, it is mainly focused on point performances, which have not been included in the multi-role sizing approach of chapter 9. Therefore, the introduction of these considerations here seems to constitute a significant prospect.

However, the use of the matching diagram per se within the initial sizing approach proposed within chapter 9 would be hindered by the workflow that this latter method follows. As it is seen from the geometric sizing step, whose content is developed in subsections 7.6.3 and 7.7.2, the value of S_w is determined via a regression with $MTOM$. Therefore, there is a constraint between these two variables that results in a specific value of the take-off wing loading for any given $MTOM$ value resulting from the previous mass estimation step. This relationship is shown in Figure 10-1.

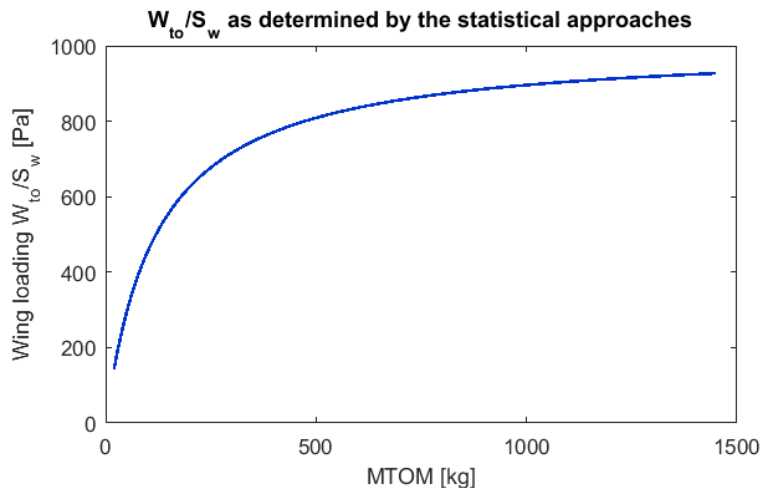


Figure 10-1. Wing loading variation with $MTOM$ for as determined by the statistical approaches.

In terms of the matching diagram, this would correspond to a fixed vertical line. Furthermore, the engine selection should also be carried out at the start of the multi-role initial sizing process since some characteristics related to the powerplant are needed. Therefore, the use of the matching diagram to select a design point within the feasible region as delimited by the constraints would not be seamlessly compatible with the initial sizing workflow, and it would require to rework the flow of the sizing process proposed in chapter 9. In spite of this, the verification of the different restrictions that are represented within this diagram can be included in the workflow in a relatively straightforward manner along with the applicable airworthiness requirements extracted with the DECEX procedure as commented below.

The constraints that were considered in the matching diagram corresponding to Figure 8-3 (which would be the ones applicable to reciprocating engine RPA as considered here)

were those of take-off, climb, landing, stall, cruise, and gust. The last of these two, which are more tightly connected to integral performance, shall be addressed further below. With respect to the others, which are linked to point performances, the values of the take-off distance, S_{TO} , and landing distance, S_L , are among the usual initial specifications of aircraft design, so they can be set by the designer in this case. Furthermore, as seen through the application of the DECEX procedure, and depending on each particular regulation, there were restrictions with respect to the minimum values of the climb rate, V_a , and the climb gradient, γ . Furthermore, some regulations also established a maximum value of the stall speed V_{so} . Considering the equations that describe each of these point performances as seen in references (7; 8; 9; 67), the level of definition of the aircraft achieved at the end of the multi-role sizing process along with a few typical values such as those that were used in the matching diagram case of 8.5.1 enables the computation of the aforementioned variables, which in turn allows to check whether the operational or regulatory requirements have been satisfied. If needed, the designer can modify some of the decisions made at the start of the process to achieve compliance through a new run of the design method, or some of the operational specifications might be negotiated.

With respect to the cruise flight considerations, the computation process expounded in 9.3.1 already obtains the power output of the engine at each point, also accounting for the ingress and egress parts of the flight, so it can be verified that this restriction is met not only in a particular point of the analysed missions segments, but along the whole flight.

Moving on to the gust requirement, in the case of the matching diagrams presented in 9.5, a restriction was established with respect to the maximum desired gust load factor, n_g , calculating when considering the gust intensities given by the regulations. The codes themselves do not establish a maximum limitation in the value of n_g that is achieved, but the structure must be sized attending to it. Therefore, in that case, a maximum desirable value was established to represent the restriction in the diagram, as higher gust load factors would lead to a reinforced structure with a larger mass (8). The matter of the impact that this regulatory requirement could have in the structural sizing process of RPA was discussed in the research of (132), where the high values that this variable could showcase particularly for small RPA were highlighted.

In this case, it is sought to introduce gust considerations in the multi-role sizing approach. Taking into account to the degrees of freedom in the initial specifications as well as the geometry of the flight profile involved in this approach, it is seen that the flight variables might show remarkable variations along the flight. For instance, the flight speed is changing through the ingress and egress flights, as they are carried out at a constant C_L , and then the mission segment can have a different flight law. This changing scenario would recommend taking into account the variation of the gust load factor along flight. This can be achieved by calculating it as an additional instantaneous variable within the computation diagram shown in Figure 9-8, as the variables required to estimate it are available in the process. Then, the most demanding gust load factor that appears within

the combination of missions can be obtained. In this case, a limit in this variable will not be established, as this is not required by the regulation itself, but its value can provide relevant insights that should be considered in further stages of the design process which would fall outside the scope of this research.

Following this approach, the different variables and restrictions mentioned beforehand can be introduced in the multi-role sizing process in a relatively straightforward manner. This allows to verify the compliance with additional design requirements pertaining to the point performances of the RPA while integrating airworthiness considerations via the use of the DECEX procedure developed in chapter 8.

10.1.3. Configuration selection approach

Configuration synthesis is one of the main steps in the conceptual design phase as commented in 2.1.2. The process through which major decisions are made with respect to the overall aircraft layout may include both qualitative and quantitative considerations. The consideration of various possible configurations in conceptual design methods has been cited as one of the foremost gaps in this field (9), which is particularly remarkable since these decisions can have a considerable impact further down the design continuum, and if only one potential layout is considered, other potentially more efficient solutions might be sidelined. Furthermore, as commented in chapter 4, one of the main features to aid in the design of unconventional configurations is the use of trade studies, which are mainly oriented in this case to compare the performance and efficiency of the atypical layout which is being studied with respect to a baseline conventional one. Considering all of the above, and particularly taking into account the layout diversity of RPA, features of the design methodologies proposed here that can aid in this configuration selection process shall be highlighted here.

Some previous design manuals and investigations on RPA have already proposed various qualitative aspects that can aid in configuration selection for fixed-wing RPA, such as the decision on whether to use tail booms to join the tail with the fuselage, or in the ways in which operational and transport characteristics may be affected by different tail layouts (6; 10; 13; 33). In this case, it is sought to propose a quantitative method that can aid in configuration selection.

As it was seen in the statistical results shown in 7.6.2, distinct configurations often show disparate trends, both in terms of regressions and histograms, so it can be an aspect that can potentially impact the resulting RPA design. In the regression-based approach of subsection 7.6.3, which is one of the two that can be used in the multi-role sizing process, the configuration has to be selected beforehand by the user, since the regressions and data to be used shall be different in each case. However, considering the rapid computation times of the multi-role design methodology, it is feasible to run it multiple times with the same requirements for various configurations. This produces a sizing result for each layout, which can then be compared amongst them so as to select the most

promising one. The outputs of the methodology include design mass variables such as the *MTOM* and also the coefficients of the drag polar, as well as the point performance and airworthiness-related results when considering the previously mentioned additions. This information can aid the designer to make a decision with respect to the most promising layout. The process proposed here can be considered to be a trade study conducted on the configuration decision while keeping the same initial requirements, which would also fit within the trends of computerised environments of chapter 4, being aligned with one of the key areas for the development of future RPA design packages as proposed in 4.6.2.

In a practical design case, the results from this evaluation should be complemented with other qualitative aspects to further aid the designer in narrowing down the most promising configuration. It could be the case that various design alternatives show similar performance, in which case, as done in previous works (43), the conclusion could be that they should both be studied at the level of preliminary design methodologies, which are more accurate, so as to make a more informed decision later on.

10.2. Application case to initial sizing of small RPA

This section contains an application of the combined approach as proposed in the previous section. This shall be done focusing on the type of missions which are conducted by small RPA, to propose a different case than those developed beforehand in previous case studies.

The configurations that will be compared shall be those of conventional tail, T-tail, V-tail, and H-tail, which are the four covered by the regression-based sizing approach proposed in 7.6.2. Considering the results previously shown in Figure 7-10 with respect to the use of the distinct tail types and the different ways to connect the tail unit to the rest of the airframe, cases with and without tail booms shall also be considered. In the case of the H-tail layout, as nearly all of the database RPA showcase it in combination with double tail booms, it shall be paired with this type of union. The other tail types present various possible options for tail union type in the mass range of small RPA, but it can be seen that the use of double booms is also particularly extended for V-tail RPA here, so this option is also chosen for the V-tail RPA. With respect to the conventional and T-tail ones, a conventional union is selected since its use is relatively extended for RPA of these types in this mass interval. This will also allow compare RPA developed with different tail union types to the ones with double booms.

Subsection 10.2.1 contains the definition of the mission specifications for the multi-role aircraft, which follow a similar schema to those shown previously in section 9.6. Then, subsection 10.2.2 showcases the results for the different configurations, as well as a discussion on the way in which this information can aid the designer to choose one of them for future design analysis.

10.2.1. Design case description and specifications

Since the aircraft sought to be designed in this case would fall in the range of small reciprocating engine RPA, its missions are selected attending to the typical values of such operations as found in the database as well as in literature sources which have covered the design of this type of RPA (10; 25). Some RPA in this mass range with the selected configurations include the Aerosonde, T-15, Penguin B, Aerolight, and XPV-1 Tern. They conduct missions of various types, including ISR, photogrammetry, payload delivery, and scientific data collection, among others.

With respect to the variables that describe these operations, two main groups have been seen: those which are more demanding in the payload to be carried, but have more moderate performance requirements; and then the missions in which the range or endurance specification is noteworthy, but the payload carried in this case has a lower mass. Therefore, the multi-role RPA to be designed here shall cover both cases. A fixed landing gear, as in the case of many aircraft in this category, shall also be considered. This will also allow to see the impact that this choice can have in the climb performance, particularly when considering that the airworthiness regulations shall establish limit values in relation to them. Take-off and landing from runway is also considered here, with designer specifications being established with respect to the usual values of these aircraft as found in the literature.

Before moving on, the airworthiness requirements with respect to the variables that are considered in this combined design approach as laid out in the previous section need to be extrated. This is done through a new application of the DECEX methodology, in this case focused on small RPA. As most possibly the resulting mass of the aircraft shall be above 25kg, the open category of operations in the frame of EASA would not be an option, as seen in Table 3-3 and Table 3-4. The specific category requires the use of ad-hoc safety assessment procedures which would fall outside the scope of the streamlined approaches developed in this thesis. Therefore, the certified category is considered. In view of the regulations scrutinished in 3.5.1, the ones considered here shall be the CS-UAS, CS-LUAS, SC-RPAS.SubpartB-01, and AEP-83, with the last of these not being accounted for beforehand in the case studies of chapter 8. The results from applying the DECEX procedure here are shown in Table 10-1.

It is seen that, in this case, there are no specific values for the climb gradient as established by the regulations. The DECEX procedure considers the option of using manned aircraft codes with similar applicability range to cover these cases, but in this scenario it is considered that small RPA would be too far from the range of mass that is typical of ultralights for this to be applied here. With respect to the rate of climb, there are two distinct values, so in this case the most restrictive one, which is the one given by SC-RPAS.SubpartB-01, is the one considered.

Table 10-1: Results summary of DECEX procedure application for the small RPA case study

Code	Stall Speed (V_{so})	Climb Gradient (γ)	Rate of Climb (V_a)	Gust Intensity (U_e)
CS-UAS	2110: M	2120: M	2120: M	N/A (refers to ADS)
CS-LUAS	N/A	53: M ^a	N/A	333: 15.24 m/s
SC-RPAS. SubpartB-01	49: M	N/A	65: ≥ 2 m/s	N/A
AEP-83	UL.41: M	UL.43: M	UL 43: ≥ 1.5 m/s	UL.5.3: ≥ 15.24 m/s

N/A: not available, **M:** Medium specificity. For High level of specificity, the limit values are declared. **a:** Limit values to be determined in accordance with the Authority, but none stated directly in the regulation.

With all of the above, the main requirements for this design case are summarised in Table 10-2. It is noted that the values of the drag polar correction factors due to landing gear and payload are different to those selected in the application case of 9.6.2, which is due to the different geometries of these components found in most cases of small RPA when compared to the ones of larger vehicles.

Table 10-2. Summary of requirements for the small RPA multi-role design case.

Mission specifications			Other considerations	
Variable	Mission 1 (M1)	Mission 2 (M2)	Variable	Value
PL	10 kg	3 kg	S_{To}	100 m
R or E	40 km	8 h	S_L	100 m
V	32 m/s	24 m/s	V_a	2 m/s
h	1000 m	1000 m	η_{LG}	0.21
R_{ineg}	0 km	50 km	η_{PL}	0.15

10.2.2. Initial sizing and comparison between configurations

The results obtained from running the multi-role initial sizing methodology for all four design alternatives commented at the beginning of this section are summarised in Table 10-3.

From a broad perspective, the RPA which have been obtained in each case share similar characteristics amongst them, and it can be seen that the point performance requirements are accomplished for all of them, albeit with different margins. However, when analysing specific groups of variables, there are various conclusions that can be derived from these results, which also link with the configuration selection decision taken for each of them.

Table 10-3. Results from the small RPA sizing case of the multi-role sizing methodology.

Variable	Units	Conventional tail	T-tail	V-tail	H-tail
MTOM	[kg]	39.69	39.58	39.27	38.02
OEM	[kg]	24.77	24.68	24.41	23.32
MPL	[kg]	10.2	10.2	10.2	10.2
MFm	[kg]	6.58	6.50	6.30	5.52
S_w	[m ²]	1.57	1.57	1.56	1.55
b_w	[m]	3.19	3.18	3.17	3.14
AR	[-]	6.48	6.44	6.44	6.36
C_{D0}	[-]	0.0412	0.0403	0.0382	0.0265
C_{D1}	[-]	-0.013	-0.013	-0.012	-0.010
C_{D2}	[-]	0.081	0.081	0.076	0.072
S_{to}	[m]	95.8	95.1	94.2	87.7
S_L	[m]	64.0	63.8	63.7	62.1
V_a	[m/s]	2.79	2.82	3.00	3.49
n_g	[-]	4.61	4.61	4.62	4.69

With respect to the mass values, these are remarkably similar for all four RPA, with the cases of conventional tail and T-tail showing only minute differences. The layout that shows the lower design mass values is the H-tail, with this behaviour being substantiated when considering the more favourable drag polar curve that is presents with respect to the other layouts. The differences in the coefficients of the drag polar are commented further below. In terms of wing geometry, all of the RPA share a similar result, since the correlations determining these aspects depend on the value of *MTOM*.

The foremost differences are seen in the coefficients of the drag polar. The layouts with conventional union of the tail unit with the airframe have the largest values of these coefficients. RPA with this type of tail union showcase higher values of slenderness, as seen in Figure 7-25, thus reducing the form factor. However, the overall greater length of the fuselage until it reaches the tail surfaces contributes to a higher value of friction drag. In the case of the two design options with booms, there is also a remarkable difference between them, with the H-tail layout presenting a significantly lower drag coefficient. This is attributed to the different values of slenderness that are seen for each layout when studying similar aircraft, with those with V-tail configuration having values around $\lambda_f = 4.5$, whereas the H-tail ones show values closer to $\lambda_f = 6.5$. This produces a noticeable difference in form factor between both layouts, thus leading to this dissimilarity.

With respect to the *C_{D2}* coefficient, the high values observed through all RPA are mainly due to the low value of *AR*, as wing vortex drag contributes a significant amount to this result. However, noticeable differences are seen through the distinct layouts. The ones with a conventional union of the tail show the highest values. This can be explained through the fuselage viscous lift-dependent drag, which is a contribution considered within the drag polar model of this research as commented in 9.3.2. The higher overall

planform surface of the fuselage, particularly due to its greater length, produces an increment in this effect. When compared to the tail boom layouts, and in spite of their reduced slenderness, the overall planform area of the fuselage is lower, leading to lower values of this coefficient. The difference between the V-tail and H-tail layout can be substantiated through the aforementioned dissimilar values of slenderness as commented beforehand.

The initial specifications related to point performances are accomplished in all cases, with the differences being mainly due to the value of *MTOM*, and in the case of the climb performance, also considering the drag polar. With respect to this latter aspect, in contrast to the high impact of the certification constraints seen for tactical RPA in the case study of 8.5.1, here the certification constraint in climb rate is less concerning than other specifications that are accomplished with a lower margin, such as the take-off performance. It is noted that the regulation demands compliance with the climb rate limit at the optimum climb C_L , which has been taken into account here. Therefore, it can be expected that in many operations the climb rate shall be lower than the values shown here, since the C_L used in these cases is in some cases relatively close to stall, so a larger margin could be desirable.

Finally, with respect to the gust load factor, and in spite of the low flight speeds as stated in the design specifications, the values are remarkably high. This is owed to the low wing loadings of small RPA, which in the particular case of the design methodology employed here, would be given by the curve shown in Figure 10-1. However, these values fall in line with those obtained in the work of (132), which studied the gust load factors for a series of existing RPA, comparing them with the manoeuvring load factor and determining that the former was in most cases significantly higher than the latter. In view of this, one of the conclusions of this research was that gust considerations could be significant when sizing the structure of the RPA, potentially leading to an increase in weight (132). This finding would also apply to the design cases shown here, and is a consideration to be taken into account when addressing the structural design in later design stages.

Overall, it can be seen that the results from the methodology provide a significant amount of information to the designer, with the added benefit of the combined method expounded in this chapter including point performance and airworthiness consideration. Overall, from the results of this design case, all four design candidates show similar performance, with the largest variations being found in the drag polar. The small differences in design mass values might not allow to substantiate the selection of one configuration or the other, particularly considering the level of accuracy of conceptual design methodologies. The most deciding factor could be the improvements in drag polar seen for the H-tail layout, as these are more significant.

However, it should be considered that this quantitative approach should also be accompanied by qualitative criteria that might depend on more specific aspects, such as those related to the operational scenario where the RPA is going to be operated, and also

transportation and assembly requirements. In this way, and particularly in this case where the results of all configurations are relatively close to each other, these additional considerations could be the ones to finally determine the choice on the design alternative. Another possibility would be to keep these four layouts until a further stage of the design process where refined methodologies and more disciplines are considered, since their accuracy can provide a more detailed view on the differences which fall outside the scope of conceptual design methodologies.

10.3. Conclusions

The combined design methodology presented in this chapter rounds off the contributions of the preceding three as part of the overall objective OBJ.3 of the thesis. This overall initial sizing process leverages the use of statistical approaches, design-airworthiness integration, and integral performance-based methods in a single workflow, with each of these topical areas contributing to different aspects and allowing to propose a more comprehensive design process.

The results of the combined design methodology do not only constitute an aid to the designer in terms of conducting the initial sizing of multi-role RPA attending to airworthiness considerations, but they also constitute a significant source of information for making design choices or even to conduct new iterations. Albeit in the case study presented here, all layouts accomplished the point performance and airworthiness requirements, this might not be the case in other scenarios, and a specific layout could be the one to comply with them. Other scenarios might arise, such as the RPA meeting all point performance requirements with an excessive margin, or even with non-converging design processes due to integral performance requirements that might be incompatible. This could lead to new iterations where the designer might adjust the engine and other input data of the model, select a different type of landing gear, or even negotiate some of the requirements to reach a more efficient solution. These kind of rapid design space explorations, configuration decisions, and iterations are all typical of the conceptual design stage, and it is sought that these approaches can aid the designer to address the tasks pertaining to this stage.

Nevertheless, as commented beforehand, it is also key to consider other types of aspects that might be crucial towards the design decisions. Configuration layout choices area also heavily dependent on qualitative considerations which are outside of the scope of the methodology presented here, so a combined use of both types of approaches would be recommended. Furthermore, the level of accuracy of the conceptual design methodologies might not allow to discern in certain cases, such as in the application scenario conducted here, which may be the most adequate design candidate. In this sense, the combined use of this sizing process with further approaches that have a higher fidelity as well as with optimisation frameworks which may aid to refine each of the layouts constitutes a promising prospect to complement the capabilities of each type of process.

Other aspects could also be considered to expand the scope of this methodology, such as the consideration of more types of configurations, the analysis of the aerodynamic behaviour of the RPA when encountering the gusts defined by the regulations so as to see if may limit the load factor that it can withstand, and the integration of different flight laws and flight profile geometries that can allow for higher variability in the mission definition. These are considered potential avenues of future work, many of which would be dependent on advancements in each of the three lines of work of this chapter, further emphasising the ways in which the capabilities of methodologies with a broader scope, such as the one presented here, depend heavily on the features of the building blocks used to create them.

All in all, it can be considered that the combined initial sizing methodology proposed in this chapter would satisfy the purpose of this third part of the thesis, constituting an overall sizing process with a broader scope than that of the different approaches developed beforehand. As seen from the results of the preceding section, it enables the designer to manage the high number of factors and considerations involved in multi-role RPA, as this can combine multiple missions with differing requirements, point performance specifications, airworthiness, etc. The nature of the methodology as a fast estimation process enables to carry out various iterations and to examine distinct choices in a short amount of time, as required in the conceptual design stage. Therefore, with all of this, it can be considered that the objectives related to OBJ.3 of this thesis have been fulfilled.

11. DISCUSSION

This chapter opens the final part of the thesis, which seeks to round off the research, insights, and analyses presented through parts II and III. As commented in chapters 1 and 2, the thesis has followed a process which started from topics with a broad scope that cover many areas of RPA design, so as to then focus in more specific subjects, since it was seen that the gaps at that level of granularity were key to address the main overall challenges of this field. Then, starting in chapter 10, a return to a higher level of granularity was carried out when assembling the distinct design approaches to form an overall initial sizing approach. In this chapter, this trend continues, as additional insights may now be drawn and discussed in view of the analyses and results for each of the topics covered in the preceding chapters, now considered from a combined perspective.

Considering the above, in the first place section 11.1 summarises some of the essential discussion points pertaining to each of the main topics covered in the thesis. Then, section 11.2 shall discuss some perspectives when considering the combination of different subject matters, now in view of the results and insights that have been obtained through this thesis for each of these areas.

11.1. Specific discussion points related to each of the topics covered in the thesis

The analyses, insights, and results pertaining to each of the lines of research of this thesis, according to the objectives established in chapter 1, have been presented through the preceding chapters. Here, some points of discussion pertaining to each of these areas are presented, expounding the main significance of the findings of the research carried out for each of them:

- **Overall landscape of RPA design methodologies (chapter 2):** as it was seen in Table 2-2, there is an uneven distribution of works to each of the topical areas pertaining to RPA design. One of the main findings was the way in which the gaps detected in certain areas resulted in shortcomings in other related topics. This has been seen to be particularly noteworthy in the connection between design approaches at different granularity levels, where the low availability of specific methodologies covering certain points (for instance, multi-role design, geometric sizing of the tail surfaces, etc.) result in hurdles with respect to these aspects in the methodologies at a higher scope level, such as initial sizing approaches or computerised environments, which are usually built upon combining the other ones that are found at a higher granularity level. This highlights the relevance of analysing the field of RPA design as an ensemble, and of considering the gaps and needs of approaches in each topical area so as to detect which are the ones where improvements could also lead to enhancements in others.

- **RPAS regulatory paradigm (chapter 3):** the regulations pertaining to RPAS airworthiness are still in their nascent stages, with most of them being relatively recent. From the analysis conducted in the chapter, it was seen that both the main philosophy and contents of these regulations are starkly different to those of manned aeroplanes. This is substantiated when considering the particular characteristics of RPAS and their operational scenarios, which result in a myriad of possible risk scenarios that are distinct to those of traditional aviation. With the goal of not establishing excessive restrictions to the potential applications of these aircraft, the Authorities have emphasised a flexible and non-prescriptive approach. However, the main characteristics of current RPA codes with respect to specificity and level of detail can result in certain particular hurdles towards integrating streamlined airworthiness requirements in design procedures. Some possibilities of surmounting these challenges could include the availability of a larger body of ADS to complement the mandatory performance-based requirements which have a lower specificity, and also the use of conventional codes to complement the specifications of those of RPA. The identification of the design integration challenges seen here led to the study in chapter 8 of procedures that could aid to surmount these issues.
- **Landscape of current design environments towards use in RPA (chapter 4):** the main results of the surveys and assessments conducted here show that, in spite of the high interest in applying these packages to RPA design, there are still noteworthy gaps towards covering the main challenges related to the development of these aircraft. The main capabilities of current environments, even of those which have added RPA-related functionalities, are focused on the characteristics of manned aircraft, which can be explained as this field in only more recently seeing an advancement in terms of RPA design. This results in noteworthy mismatches between features that are currently available in these packages and the needs of RPA conceptual design. For instance, it was seen in Figure 4-12 that layouts which are common in RPA, such as V-tails and H-tails, were seldom considered in current environments. Furthermore, a higher degree of mission definition flexibility that can adapt to the wide array of possible operations of these aircrafts would also constitute a noteworthy asset, as most packages are focused on missions pertaining to transport aircraft. To enhance these aspects, it is first required to develop methodologies compatible with these features, which can then be integrated in the design environments, leading to the focus of part III of the thesis on topics at a finer granularity level that can aid in covering these gaps. Furthermore, a remarkable interest in computational advancements was seen among the main trends. In spite of this, current data models and exchange processes could also be enhanced through the use of approaches based on KE and AI, which was one of the main reasons leading to the line of research developed in the subsequent chapter.

- **AI topics related to airworthiness and design (chapter 5):** considering the high safety standards in aviation, the use of AI in this field should consider the particular risks that might arise from the application of these methodologies, so that their remarkable potential can be leveraged while maintaining the level of safety of the system. As seen from the documents published until now by the main Authorities, the emphasis is on capabilities related to explainability and trustworthiness. However, different AI models show distinct characteristics with respect to these concepts, with those of the symbolic type being more aligned with them. Considering this, and also taking into account the recent emphasis on data models and KE approaches in computerised environments, the use of ontologies to enhance communication, interoperability, and engineering aspects was studied. Up until now, very few ontologies have been developed in the overall field of aircraft design. In contrast, the analysis of the characteristics of design environments that could be enhanced through ontologies reveals remarkable prospects in the use of these semantic artifacts within this field, providing potential enhancements in terms of model consistency, data exchange, reasoning capabilities, and system modelling, among many other possibilities. This emphasises the interest in further studying this area so as to leverage the potential of these semantic artifacts to improve the capabilities of design environments.
- **Gaps and needs towards initial sizing methods of RPA (chapter 6):** here, the thread of the gaps seen in higher granularity design approaches was traced back to the topical areas with a more specific focus which are used as building blocks to create the first ones. In view of the findings of previous chapters, a set of objectives was established in terms of the aspects that should be covered by topical areas at a fine granularity level so that the main hurdles seen in more comprehensive methods could be addressed. Key issues in current design procedures related to statistical approaches, airworthiness-design integration, and integral performance-based sizing were detected. These potential areas of improvement helped to establish the main goals for the novel design approaches to be developed in the subsequent chapters.
- **Statistical approaches for RPA design (chapter 7):** the foremost hurdle towards developing these kind of methodologies is the comparative scarcity of data pertaining to RPA. As seen in Table 7-3, while general variables that describe the aircraft are relatively easy to find, more specific characteristics such as the dimensions of tail units and fuselage are remarkably scarce. It was deduced that this could also be the main reason for these variables not having been covered in previous statistical analyses of RPA. As it was seen through the statistical analysis conducted in the chapter, the sample size can be remarkably reduced if a data matrix containing these variables is to be studied. In these circumstances, the use of hypotheses tests and of statistical metrics is essential to ensure the significance

and usability of the results. In view of the regressions and other results obtained from the database, one of the main takeaways is the influence that aspects related to the configuration (such as tail type or tail union approach) can have in the results, showing at times very dissimilar trends. This emphasises the need of considering the RPA configuration, which is one of the aspects showing the largest diversity for these aircraft, when performing statistical analyses of RPA. The results obtained for both of the proposed sizing methodologies achieved satisfactory levels of accuracy for conceptual design, emphasising the potential of such methods in the initial stages of RPA development.

- **Design-airworthiness integration for RPA (chapter 8):** in view of the findings of chapter 3, the current regulatory paradigm can showcase significant hurdles towards including streamlined airworthiness requirements in RPA design methods. Considering the broad range of possible sizing approaches and the diversity of regulatory requirements, the DECEX procedure proposed in this chapter enables a flexible schema that can be applied to many types of design methodologies. Its application was demonstrated to the matching diagram case for two types of RPA. As seen in the results presented in Figure 8-3 and Figure 8-4, the feasible design can become remarkably constrained when adding airworthiness considerations. Therefore, it is deduced that, when considering the certification of the RPA, significant modifications to the design space may arise, so they should also be considered from the onset of the process, since the impact on the resulting aircraft can be significant.
- **Initial sizing of multi-role RPA (chapter 9):** considering the fact that the diversity of missions that RPA can accomplish as well as their multi-role nature are among the foremost features of these aircraft, the development of a methodology that can account for these aspects constitutes a significant prospect. The possibility of evaluating not only overall aspects related to each flight represented in the PL-R and PL-E diagrams, but also the behaviour of distinct variables along each of these flights, has revealed that certain regions of the mission space may not be feasible, which is not caused by mass limitations, but rather by certain variables such as C_L or Ω_E exceeding their limits at some point of the flight. One of the foremost results was the way in which the diagrams changed upon modifying certain design or operational parameters. The nature of these modifications were very different, highlighting that depending on the desired variations in the mission space of the RPA, certain changes may be more advantageous than others. For instance, to enable missions with a higher payload but a similar range to existing ones, changes in OEM would be the most desirable, as seen in Figure 9-25. In contrast, when seeking to add more range or endurance missions, other type of modifications might be preferred, such as the reduction of the C_{D0} drag polar coefficient through the improvement of payload and landing gear characteristics, for instance. Finally, with respect to the multi-role sizing

approach, its results showed that accounting for various simultaneous requirements of differing missions has a remarkable impact on the resulting RPA, with the multi-role one being much different to the single-role designs for each individual operation. Furthermore, the different missions can interact in complex ways depending on their specifications. For instance, there can be a particular mission which can be driving the increase in RPA mass since it is much more demanding in terms of MPL or of performance than the others. Thus, providing the designer with information with respect to the ways in which each mission influence the resulting aircraft is a key prospect to aid the designer in conducting the requirements analysis and also for potentially negotiating the specifications.

- **Combined approach for multi-role design and configuration selection (chapter 10):** as seen when addressing the integration of the different design approaches developed through part III of the thesis, the consideration of modularity and workflow compatibility aspects when developing the individual methods is a crucial asset towards aiding to integrate them within a more comprehensive method. The flexibility of each of the approaches developed beforehand, as well as the agreement between their applicability considerations constituted key aspects when conducting their integration in this chapter. The results of the methodology show that taking into account performance specifications and account airworthiness considerations is crucial towards enabling a more holistic view of the aircraft's feasibility, and the use of rapid calculation procedures is significant towards enhancing the design space exploration and concept iteration. Finally, within the level of accuracy of conceptual design, the methodology provides tools to conduct a comparison between various layouts, which is a remarkable prospect when considering the variety of this feature among distinct RPA designs.

11.2. Overall discussion of topic connections and common considerations

As seen both in chapters 1 and 2, as well as through many points of the thesis, the distinct topics covered here are strongly connected to each other. As a result, the distinct lines of research have influenced one another in significant ways, with the findings of some of them being key to determine the research directions of the others. For instance, as seen in chapter 6, the study of the gaps in RPA design through different areas had a crucial impact in the decision made to focus on the three specific areas of RPA conceptual design that were studied in part III. Furthermore, the aspects that were studied within part II have also been fundamental to pinpoint the aforementioned gaps, and also to direct the efforts of the novel methodologies towards areas and features that are relevant towards their potential integration in future design environments.

Thus, having already expounded the analyses, results, and insights of the different chapters, here a more holistic discussion with a broader scope is developed. The emphasis shall be mainly on those aspects that have showcased strong interrelationships among the different areas, so as to highlight the ways in which the complex connections between the individual topics have been fundamental in this research.

With respect to the ways in which the topical areas connect, it has been seen that a majority of works of the GDM type, save mainly for those pertaining to design manuals, have mostly focused on a particular subject matter. However, when the objective is to build methodologies that cover a broader scope, such as overall initial sizing approaches and computerised environments, it is essential to observe the current gaps in the methods that are found at finer granularity levels, because their capabilities have a direct impact on those that are more encompassing. This has been one of the main points leading the thesis to study topics at distinct levels of granularity. For instance, scrutinising the current landscape of RPAS regulations was a substantial foundation towards the design-airworthiness work developed in chapter 8, as it was first needed to detect the ways in which the characteristics of present regulations could affect their use in streamlined design procedures. The study of distinct topics at the same granularity level, as it has been the case in part III, has also been essential, as this has enabled to observe integration aspects among them so as to then build an initial sizing approach from their combination. Therefore, it can be deduced that considering other aspects and influences outside of a particular topical area can be essential to enable both the integration of the different approaches in a more holistic framework, and also to detect the ways in which the gaps of the different subject matters interact, so as to cover in the first place the points which may be influencing other areas in the first place. It can be considered that one of the main features of the research presented in this thesis has been the consideration and study of these connections among topics.

One of the areas showing a larger degree of interrelationship with others is that of computerised environments. This can be owed to the fact that these packages often constitute holistic tools that cover many different topical areas of the aircraft design process. Furthermore, one of the main areas of interest in relation to these environments is constituted by computational aspects, which are being increasingly considered in recent times, and they have been shown in Figure 4-8 to be key enablers to other noteworthy trends, including the design of RPAS. This also opens a series of remarkable interrelationships with other areas such as software engineering and even AI. The possibilities of KBE approaches and of common database models were among the main reasons leading to study the potential uses of AI-related approaches in chapter 5. Furthermore, the coincidences seen between the gaps present in other RPA design works at finer granularity levels and those of computerised environments led to reinforce the perspective that improvements in specific topical areas would be required to improve current design environments in terms of RPA design.

Regarding the field of AI, this is one of the key topics explored in this thesis since it shows noteworthy connections with many others ones. The evaluation of the potential of the use of ontologies within computerised environments yielded significant results, with these type of semantic artifacts constituting a promising prospect to address some of the current hurdles of this area. On another but related subject, the relationship of AI with aviation safety, and thus with aircraft and RPA regulations, is also noteworthy, since the potential risks that may arise from the use of AI methods are remarkably different to the ones that are usual up until now in traditional aviation systems. A very strong connection with RPAS regulations was detected, analysing the ways in which the regulations on both sides could become interrelated in the future.

Some connections between the topic of AI and the area of statistical studies of RPA are also discussed here. Albeit subsymbolic AI approaches were not the focus of the work presented in this thesis, it was seen that some previous works had leveraged these models in terms of developing surrogate models, and also for the extraction of trends of existing RPA. However, it is noted that, from the findings of this thesis, this second avenue of work would face relevant difficulties, since the issue of data scarcity, which was encountered and discussed in chapter 7 of this thesis, would also affect these kinds of methods, potentially limiting their use to the study of general design variables which are typically found in the literature. Therefore, unless the data scarcity issue related to existing RPA designs can be surmounted, it would appear that the use of these models in areas such as the development of surrogate models from high-fidelity approaches constitute more feasible and promising perspectives nowadays.

With respect to the novel design approaches proposed in part III of the thesis, one of the main considerations through their development has been observing the ways in which models that are currently extended in manned aeroplane design could fit with the main challenges and characteristics of RPA. This links with one of the main guiding threads of the thesis, which is that of method applicability, as introduced in chapters 1 and 2. Therefore, through the development of chapters 7, 8, and 9, there has been a significant effort in developing new approaches which are aligned with the essential features of RPA, so as to ensure that their use can enable to achieve believable results when using them to design these aircraft. Several new considerations have been taken into account through these chapters so as to develop the methodologies proposed here in such a way that they can address some of the foremost hurdles in this field, as introduced in 1.3. Therefore, aligning the hypotheses and capabilities of the models with the challenges and peculiarities of RPA has been one of the main guiding threads of this part of the thesis as a whole. Figure 11-1 provides a summary on the main adaptations and considerations applied to the methodologies developed in part III as well as the features and challenges of RPA, when compared to those of manned aircraft, which motivated these changes.

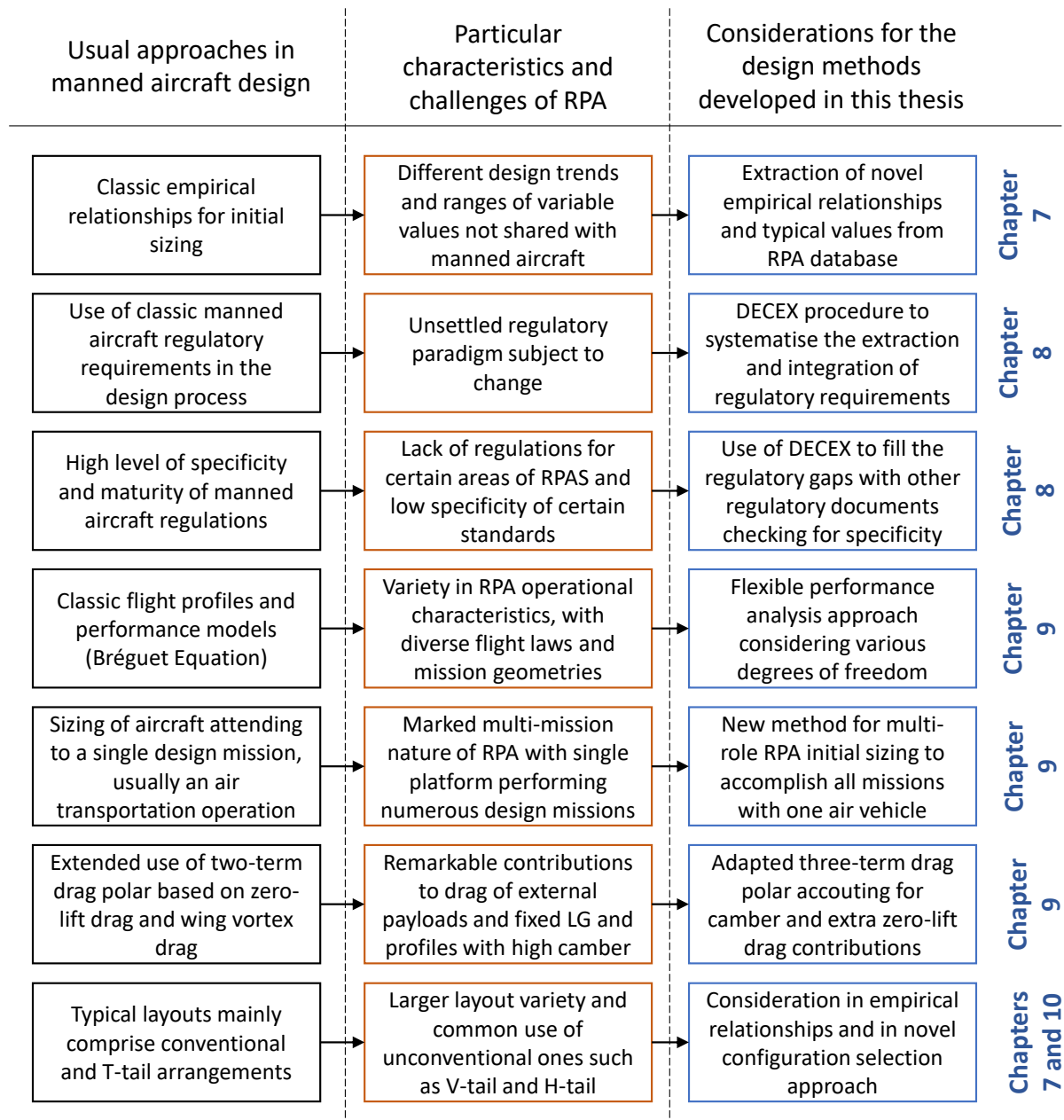


Figure 11-1. Summary of model adaptations when considering the challenges and peculiarities of RPA.

Overall, the high level of coupling among the distinct topics covered in this thesis has been one of the main pints that have influenced the research directions and content of this research. The additional discussion provided here prepare the ground for the conclusions to be developed in the following chapter.

12. CONCLUSIONS AND FUTURE RESEARCH

The final chapter of this thesis presents the conclusions of the research, as well as some comments regarding key avenues of future work.

In section 12.1, each of the three main design approaches developed in this research is addressed, and specific conclusions are drawn for each of them. Then, in section 12.2, the main forthcoming line of research which builds upon the results of this PhD thesis is expounded. This future work returns to the topics of computerised design environments and applications of AI within conceptual design which were discussed in part II. Using the design methodologies developed within this research, and applying the opportunities of ontologies that were proposed in chapter 5, a computerised design environment for RPA which can leverage the potential of ontologies is envisioned here. Finally, subsection 12.3 links back with the objectives that were set at the start of this PhD thesis, drawing the overall conclusions of the investigation and proposing further avenues of future work, all within the overall context of RPA design methodologies that has served as the background for this investigation.

12.1. Conclusions on specific topics of the research

The overall conceptual design methodology for RPA which is the main output of this research is a result of the combination of three very distinct lines of research, developed within chapters 7, 8, and 9, each of which constitutes a standalone design approach focused on a particular discipline. Thereby, in this subsection, the specific conclusions from each of these individual lines of research are expounded.

12.1.1. Statistical methodologies for RPA conceptual design

Statistical relationships and approximations have a key role within aircraft conceptual design methodologies, as they are suitable for the estimations and rapid sizing approaches that are commonly used within them. Taking this into account, the compilation of a database of fixed-wing RPA, its statistical analysis and the derivation of novel empirical relationships for RPA constitute one of the key parts of this research.

The data gathering process and the analyses conducted on the resulting dataset have revealed key challenges in the process of deriving statistical results within the field of RPA design. In particular, the main obstacles that have been found were: **(1)** data scarcity (for instance, tail surface geometric parameters are very difficult to come by), **(2)** lack of data specificity (for example, the flight conditions associated with a stated endurance value are not given), and **(3)** conflicting data among different sources (such as different values for MTOM being stated in distinct sources for the same air vehicle variant). All of these have a direct impact in the statistical analyses which can be conducted on RPA datasets, and not only within the scope of the research presented here. For instance, as commented

within the state-of-the-art of chapter 7, there are currently very few statistical results related to fuselage dimension and tail surface geometry of RPA. Upon the results of the analyses conducted within this thesis in relation to the aforementioned challenges, it can be expected that this is a consequence of these issues. Thereby, until data on RPA becomes more widely available within the open literature, it is likely that the issues commented here will also affect future statistical research on RPA design, particularly those analyses that are conducted employing multivariate techniques, as it was also seen in chapter 7.

Taking into account the challenges commented beforehand, the development of the statistical methodologies in this thesis has sought to surmount or mitigate them as much as it has been possible. In the data gathering process, measurements were taken from three-view drawings to complete information on fuselage and tail surface geometries. In spite of this, statistical analyses had to be restricted to those tail layouts and powerplant categories where the most amount of data was available, as it was only possible to ensure statistical significance for some of the data subsets. This way, regression analysis was applied to conventional tail, T-tail, V-tail and H-tail RPA, which had a sizeable sample size within the full dataset. In contrast, factor analysis was only feasible to be applied for the category where the most amount of data was available, which is the H-tail category, as being a multivariate technique, any aircraft which is missing even one of the parameters to be studied has to be omitted, since a full data matrix is required. Within the factor analysis study, two analyses were performed: one with variables for which data is typically available, and another for parameters that are of greater interest for sizing methodologies, but for which fewer data was found. Following these steps, statistically significant results within the margin of error allowed in conceptual design were found, and novel rapid sizing empirical relationships were extracted.

However, even if the aforementioned approaches were useful towards reaching relevant results adequate for the conceptual design stage, it is acknowledged that the ideal case would be to have a more complete dataset, as the lack of data volume ensues some limitations within the analyses and results that have been attained. Some of the correlations, particularly those of the V-tail category, in spite of presenting adequate statistical figures, have a low number of data points. Thereby, a future line of improvement would be to estimate these correlations with a larger number of aircraft so as to ensure their robustness. Furthermore, with a larger number of data, different classifications could be tested in the correlations to check whether segregated regressions could more adequately fit the categories rather than a combined one. For instance, classifications according to launch and recovery methods could be established in the wing loading correlation, as this parameter, through the matching diagram, is related to those categorical aspects. With respect to multivariate techniques such as factor analysis, accounting for the simultaneous variance of many variables is key within their approaches. Considering this, when applying the parameter trimming strategy which was used in this research, some relevant dimensions of variance might have been lost. Thereby, a larger dataset could not only allow to use this technique with different

configurations to extract their underlying design trends, and checking if they are similar to those presented by the H-tail layout, but also the confidence and robustness of the results could be further assessed.

With all of this, it is clear that the expansion of the database is one of the key lines of future improvement in this area. It is expected that as the field of RPAS matures, more data will become available, and it will also be of higher quality. Considering the rapid evolution of this field, it is probable that in a few years time, a much more robust and complete dataset can be compiled. Another possible way to expand the database, would be to develop techniques to take measurements within photographs, as albeit three-view drawings are difficult to come by, there is a large number of photographs for many of the RPA within the database. This could allow to complete some of the entries of the database. However, this approach would have to be developed with caution, as it is not desired that measurement errors distort the database results. Photographs can have significant distortions, and the technique to estimate certain geometric parameters from conical perspective representations would have to be carefully evaluated. Finally, another promising avenue for the development of more complete and accurate databases shall be presented in section 12.2 along the main line of future research towards the development of a RPA computerised design environment employing ontologies.

12.1.2. RPAS regulations and airworthiness-based design approaches

As it has been seen, the area of RPAS regulations is one of the most dynamic within the field of RPAS. Most of the international Aviation Authorities have already laid out the main structure and paradigms establishing their approach towards RPAS design and operations, and certain key regulations are already in place. However, the full RPAS airworthiness system is still under development, particularly within the civil framework, and there are many rulemaking areas in progress. Taking this into account, many changes can be expected in the following years. Therefore, both from the perspectives of airworthiness and design, the regulatory evolution should be observed with attention in order to adapt methodologies and designs to its advancement, so as to ensure that the design methodologies and the products resulting from them are compliant with this evolving framework and their safety and regulatory compliance can be ensured.

One of the main conclusions extracted from the regulatory review conducted in chapter 3 is the fact that most RPAS regulations present a lower level of specificity compared to traditional ones for manned aircraft. This has relevant outcomes in the way that regulations affect design activities, and different perspectives and challenges resulting from this were discussed in chapter 3, where two main viewpoints were expounded: the first one considered that less prescriptive constraints on the design are positive as it enhanced creativity and the opportunity to exploit unconventional configurations. On the other hand, it has been seen that regulatory constraints often aid the designer in reducing the expansive of design to a more manageable size, and at the same time, they provide an

explicit and more immediate certifiability assurance when contrasted with performance-based requirements. However, since most of the regulations of RPAS are performance-based, these kind of explicit certification constraints are not usually found within this paradigm. Taking these two perspectives into account, the DECEX procedure developed in this research has been created with flexibility in mind, and can integrate restrictions both from directly applicable regulations to the RPA category that is being considered, and also from other related regulations which, albeit not directly prescriptive for the category of RPA of study, can serve as Airworthiness Design Standards (ADS). In this way, the designer can compare the available design space when considering only the applicable regulations, and also that which results when adding the requirements of the ADS. With this, and considering the design requirements of each particular case, the designer can make an informed decision on whether to integrate additional requirements as ADS in the design and certification process, thus being compatible with the two viewpoints commented above depending on the designer's preference.

During the past years, different airworthiness-based design approaches for RPA have been developed, as analysed in chapter 8. However, with the change in regulations, most of them are no longer applicable. This is the main reason why the DECEX procedure has been developed allowing to flexibly integrate regulatory constraints. This way, when regulations are updated, the design methodologies developed employing DECEX can also be modified in a simpler manner.

Within the scope of this thesis, focused on conceptual design, two case studies were developed for the development of initial sizing approaches for RPA in the tactical and HALE categories. Particularly, the case of a new matching diagram method was considered, as this is a classical technique within the initial phases of conceptual design. Through the DECEX procedure, the regulatory constraints of different potential sources were integrated. It was shown that the design space is very strongly influenced by the considered regulatory limitations, thus it is shown that having explicit information on how the different regulations restrict the allowable values for the wing loading and power-to-weight ratio constitutes a relevant asset for the designer.

However, there are still many other different areas of airworthiness-based design methods where the DECEX procedure could be applied. For instance, the influence of the airworthiness requirements from different regulations on manoeuvring envelope, gust envelope, and certification loads could be analysed, as structural design is also one of the traditional areas of airworthiness-design integration. Furthermore, many RPAS regulatory requirements are focused on reliability and systems engineering requirements, which could also link with key safety assessment techniques such as Fault Tree Analysis (FTA) and Failure Mode, Effects and Criticality Analysis (FMECA). Albeit structural and systems engineering considerations are usually taken into account further in the design process, they are two promising avenues of future research in RPA design methodologies, and particularly in airworthiness-based design approaches. Furthermore,

by using the DECEX procedure for the regulatory requirement extraction and design procedure development in other cases pertaining to different disciplines, this technique can be tested to a greater extent, and improvements to it can be made depending on the results of these prospective application cases.

12.1.3. Multi-role RPA integral performance analysis and design

The increasing diversity of missions in which RPAS are being applied nowadays, as well as the heightened interest within the state-of-the-art on multi-Role RPA have been the main drivers for the development within this research of an approach towards sizing of multi-mission RPA.

In order to conduct this, firstly, a new integral performance analysis approach was required, owing to the many dimensions of variability of RPA mission parameters which are not as prevalent in conventional manned aircraft. Most manned aircraft approaches estimate the Payload-Diagram for only one flight law and with a fixed mission profile. Here, a generic mission profile that can cover many actual RPAS operations and which has a variable ingress-egress range is applied, and two different flight laws are considered, each allowing for variability in the relevant flight parameter. This flexible framework for performance estimation has allowed to discover some relevant insights regarding RPA integral performances, such as the remarkable differences that the flight law used causes in the behaviour of the diverse flight variables that have been considered, the high sensitivity of the full PL-R and PL-E diagrams to changes in the flight law parameter chosen and to the ingress-egress range, and potential restricted areas within the mission diagrams that can arise when taking into account aerodynamic and propulsive limitations. Furthermore, the performance estimation methodology has allowed to conduct sensitivity studies analysing changes in the full PL-R and PL-E diagrams upon modifying relevant aircraft and operational parameters, such as the Operating Empty Mass (OEM), the Reserve Fuel percentage, and the different drag polar terms, which have revealed relevant insights on the influence that these aspects can have on the allowable mission space for RPA.

The multi-role initial sizing methodology uses as a basis the integral performance analysis tool mentioned beforehand, and integrates it along a geometric sizing routine which employs the statistical relationships obtained in chapter 7, and a semi-empirical drag polar model which has been derived from previous conceptual design drag polar estimation approaches taking into account some particular characteristics of RPA. Upon stating the initial requirements for each of the missions, which allow for flexibility regarding flight profile characteristics and flight law, this ensemble allows the designer to conduct an initial weight estimation and geometric sizing of RPA which can comply with the full set of missions. Furthermore, as this approach is compatible with both single mission as well as multi-mission designs, it allows for a direct comparison between the resulting aircraft when designing a single vehicle for the full set of missions, and the

alternative of conducting an individual design for each of the individual operations. As one of the main conclusions, it was seen that an RPA developed for each of the individual missions of the specification set is more efficient than the multi-role one, so there is a trade-off between mission flexibility and operation efficiency.

This integral performance estimation method and multi-role sizing approach have been developed for piston-engine RPA with fixed-pitch propellers, as they were found to be the most sizeable group within the RPA database compiled and commented in chapter 7. However, improvements to these models in order to cover the full design variability of RPA shall be conducted in the near future. Albeit piston-engine RPA are the main category, the methodology would greatly benefit from expanding its applicability to electric motor and airbreathing engine RPA. Furthermore, and albeit hybrid engines for RPA are still uncommon, these improvements could lead to developing a hybrid-engine analysis and sizing approach which would adjust the degree of hybridisation to achieve the best possible performances. These improvements could allow the method to be broadly applicable to nearly the full spectrum of RPA categories, and also permit further comparisons between them, as well as studies evaluating possible improvements upon changing the powertrain system.

12.2. Future work: integration of RPA design approaches in computerised environment enhanced by ontologies

In the previous section, key conclusions, as well as future lines of work and improvement were expounded in relation to each of the main three conceptual design approaches developed as the main results of the research presented in this thesis. However, as commented in chapter 6 and shown within the combined design approach in chapter 10, these approaches can also be combined into an overall conceptual design methodology with a higher breadth. This allows that leverages their individual potential and allows to reach a level of definition of the design concept which is compatible with proven conceptual design approaches of previous authors. Thus, the resulting aircraft definition that is achieved by employing the ensemble of the three approaches be used as an input for further design stages, such as preliminary design.

Furthermore, both the three design approaches as well as the overall conceptual design methodology developed here serve as a foundation for a more ambitious project, which is the development of a computerised design tool for RPA design. As it was seen in chapter 4, the current state-of-the-art of aeroplane design packages presents a noticeable gap in this area, and in particular in relation to conceptual design. One of the main issues, as commented there, is that the analysis and design methodologies that are currently integrated in many design environments have not been specifically developed for RPA, thus the applicability of the majority of current design software to RPA can be questioned. The first step towards elaborating a computerised design environment is to have a set of different disciplinary analysis and design approaches which are then to be integrated

within the software tool. Thereby, aside from tackling the overall gap which was detected in RPA conceptual design methodologies as shown in chapter 2, one of the main purposes of the research conducted in this thesis has been to aid in the future development of conceptual design software environments for RPA.

Albeit the development of a computerised design environment based on the three methodologies proposed in this thesis has not been possible within the time-frame of the doctoral studies, the main foundations required for its future elaboration are currently in place. Firstly, the three conceptual designs have been finalised and tested, barring the possible updates and improvements mentioned in the previous subsection. Their combined use already enables to reach a conceptual definition of the aircraft being design which is adequate as the output of the early conceptual stage. Furthermore, as mentioned in chapter 6, these approaches were developed following a modular approach, and one of the main reasons for doing so was precisely to enhance their future integration in a computerised design tool. The disciplines selected when developing these design methods, as well as key decisions, such as focusing on the categories of RPA with a higher number of aircraft presently available, in order to enhance the applicability of the methodology, were also chosen attending to the guidelines for the development of future RPA design environments as proposed at the end of chapter 4.

Additionally, and in view of the outstanding advantages that ontologies could provide in many areas of aircraft computerised design environments, as proposed in chapter 5, it is envisioned that this forthcoming RPA design software tool is enhanced through the use of ontologies. The survey of ontologies conducted in chapter 5 has identified the current environment of semantic artifacts which would be the starting point to develop new ontologies for their use in the mentioned RPA design package. As within ontology engineering activities, the analysis of previous semantic artifacts and their reuse is one of the main steps towards the development of new ones, this survey can be used as a starting point for this future line of work.

Therefore, albeit the development of this computerised tool constitutes a large task which has not been possible to tackle in this thesis, here all the diverse findings and developments achieved during the thesis could be employed as a foundation towards this future line of work. The connections between the different points mentioned above, and how the different areas that have been developed in the thesis connect with this future task are illustrated in Figure 12-1.

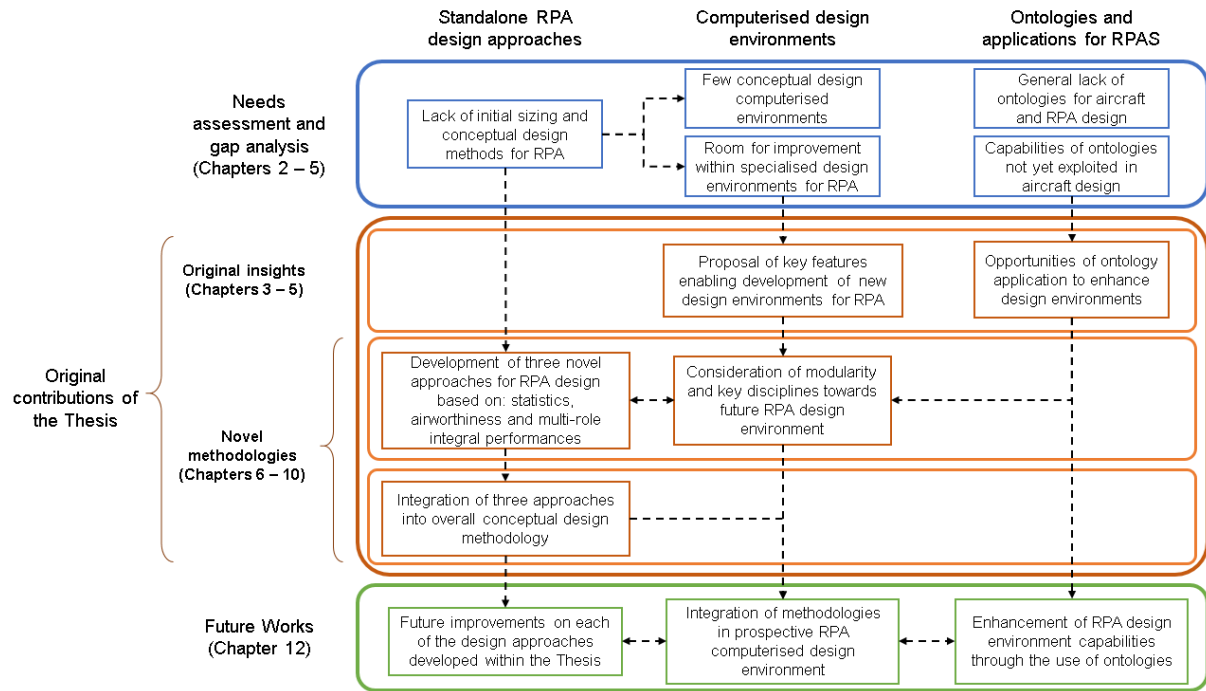


Figure 12-1. Connections among the needs assessment areas, the main contributions of the thesis, and future lines of research.

Therefore, in the following, the main steps and considerations on how this line of work connects with the developments already achieved in the thesis, and the prospective opportunities and advantages that this computerised design tool could provide, are developed below.

The proposed architecture for this tool would present a modular paradigm, as it is usual of current computerised design environment. Furthermore, this modular architecture is compatible with the fact that the three design approaches developed in this thesis have been separated precisely in order to ease their integration in a framework of this kind. Additionally, a central geometric module is envisioned, once again in the vein of current design packages. However, the main novelty would be that, in this case, the central definition of the aircraft, as well as the management of connections to the different modules, would be represented through an ontology. The different design and analysis approaches would connect to this central module, and the information on the aircraft would be updated within the central ontology, thus enabling other possible tools to be employed. In short, ontologies would be the main information representation and data exchange format, as it is commented shortly below. A simplified workflow representing this schema is shown in Figure 12-2.

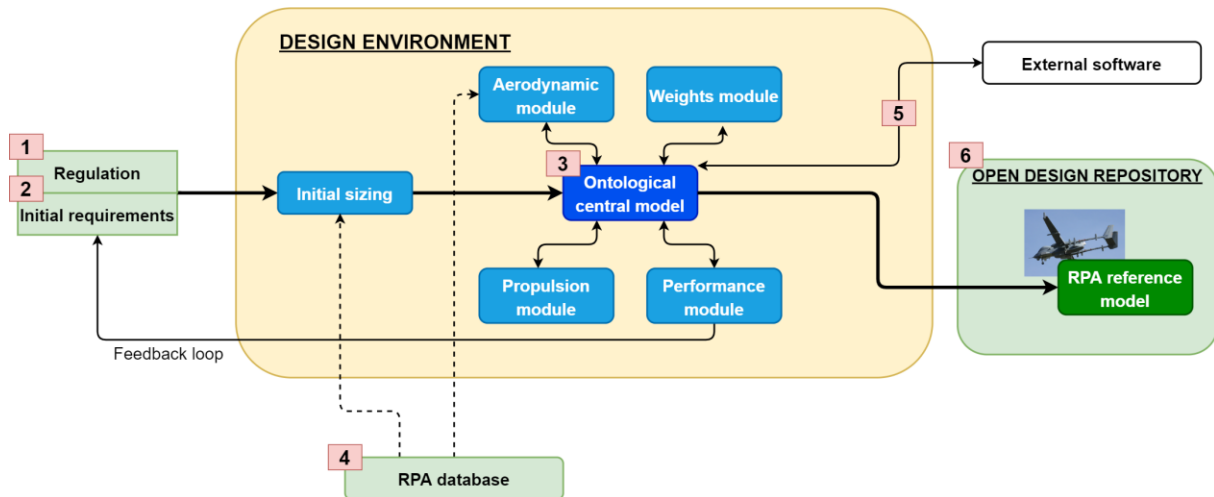


Figure 12-2. Example schema of the proposed computerised design environment for Remotely Piloted Aircraft (RPA). The numbers identify the different areas where ontologies would be incorporated. Heron 1 aircraft image from: [commons.wikimedia.org](https://commons.wikimedia.org/wiki/File:Heron_1.jpg).

In the following paragraphs, the schema is explained in more detail. The process would start, in the same way as the full design methodology presented in this thesis, with a series of initial specifications, which consist of the one hand of regulatory requirements and on other hand of initial mission requirements, which are related to the performance of the aircraft. The latter can be defined employing the multi-role mission definition schema proposed in chapter 9. From the initial specifications, a first sizing process is conducted. This sizing process would employ the statistical models obtained from the RPA database employed in this thesis, and could also employ the point performances matching diagram methods that have been developed in chapter 8 as a specific application of the DECEX methodology. This initial sizing of the aircraft results in a parametric model, which is converted to an ontological representation that serves as a common node for the following iterative process.

The different internal modules would be connected with the ontological model, from which they get the data needed for their analyses. For instance, the aerodynamic model would be represented by the drag polar model used within the multi-role sizing approach of chapter 9. In the same vein, the weight module would include the target mass estimation approach which is the first step of the multi-role sizing methodology, and the propulsion model would integrate the simplified propeller and engine models used in the cited approach. Using the central model as the main node, the aircraft definition could be updated with the different steps of the sizing methodology as they are being run, and then the performance model would evaluate if the target multi-role requirements have been reached. By comparing the result of the performance of the design RPA with the objectives in the initial requirements, the degree of compliance with these objectives can be established, and another loop can begin through tweaking the design values in order to arrive at better performance results. Optionally, an optimisation infrastructure could be employed with this same architecture in future work, albeit this would be more geared

towards preliminary design phases. The central ontological model would also allow to connect with external tools which could perform specialized analyses as needed, as connectivity with external software is also one of the main key trends of computerised design environments.

Finally, once the design process has converged, the ontology representing the system could be uploaded to a public repository of reference models on the Web which can be employed as a basis for future studies. This last point would refer to a repository such as the Central Reference Aircraft data System (CeRAS) by Aachen University, which is a Web platform that stores reference models for conventional air transport aircraft, serving as a reference for research activities. Uploading these aircraft representations through ontologies would also enable to leverage the potential of Semantic Web applications in this database, some of which were expounded on chapter 5.

Having identified the main interfaces and modules within the proposed schema and taking into account the established workflow of tasks and information, the advantages that ontologies can provide in the specific points marked in the image shall be analysed.

- 1) **Selection and specification of regulatory requirements:** albeit this is not a case application exclusive of RPAS, since it could also be applied with manned aircraft regulation, it is perhaps in the field of RPAS where it can achieve the greatest benefits. This is due to the aforementioned dynamic and heterogeneous nature of RPAS regulations. Therefore, since the initial specifications affect the whole design process, it would be beneficial to establish a clear and unambiguous definition of these restrictions, which can then be cascaded to the different design applications taking advantage of the connectivity capabilities of ontologies.
- 2) **Flexible definition of initial requirements:** in the line of the previous application, and as mentioned through this thesis, RPAS can develop a wider variety of missions when compared to traditional manned aircraft. Each mission type will be defined by different parameters, being endurance more critical in an Intelligence, Reconnaissance and Surveillance (ISR) mission than on a payload delivery one. By employing an ontological description of these requirements, at model level they can be linked with the variables of the design process which are influenced by these initial specifications. For example, the specification of endurance can be linked with the specific consumption of the engine on the system model, since this performance variable is highly dependent on the aforementioned engine parameter. For instance, some RPA can be constrained due to geometric limitations for transportation, whereas others intended to take-off and land in prepared runways might not have this restriction. The key would be in connecting the concepts which represent initial requirements with the system variables with which they are interlinked. This can allow through querying and reasoning to extract all variables affected by a certain initial requirement, amongst other applications.

- 3) **Ontological central model:** in the same vein as the central data and geometric models which are commonplace in current environments, a common node which represents the state of design of the system shall be established in the centre of the design process. Each module can connect with this ontological module seamlessly, allowing to take advantage of the reduced number of interfaces. The modular architecture of the software is required, particularly in the case of RPA design, where certain analysis blocks might have to be interchanged with others more suited to the particular configuration which is being sized, or even of the current design stage, if multi-fidelity applications are envisioned.
- 4) **Database integration:** many methodologies which have been developed for the rapid initial sizing of RPA have their origin in databases which have been compiled by the authors, as is also the case of this thesis. Therefore, databases can be incorporated as part of the design process. Usually these databases yield statistical models that are employed in the initial sizing module, however they can also be employed to extract models geared towards the modules of particular disciplines, for instance, the weight estimation module. Ontologies can infer and harmonize databases with different technologies, such as Relational Data-Bases (RDBs) and spreadsheets. These differing formats can be integrated by employing mappings and translators. If the Linked Data paradigm is also taken into account, distributed queries can be made if the data is publicly available, and the reuse and integration of databases is greatly fostered. Furthermore, the aircraft already in the database can also be represented through ontological models, as it was mentioned beforehand. One proposed application would be to implement the ontological representation of the RPAS which is similar to the one that is being designed with respect to missions and layout, and use these ontologies as a reference model for the development of the new design.
- 5) **External software interoperability:** this application would be in the vein of the general ontology benefits for computational design environments expounded on Chapter 5. Through the conceptual definition of the inputs and outputs of the external software, these can be mapped to the corresponding entities of the instance aircraft which is being designed. Consistency checking can be applied in order to assure the compatibility of the tool with the particularities of RPAS. Furthermore, this allows to encapsulate the proprietary design environment from changes in the external software, in such a way that only the translator would have to be modified.
- 6) **Modelling an open design repository:** when the design of the RPA is finalised, the advantages of ontologies can still be exploited. By incorporating the design to a Web repository, where it will serve as a reference design for future investigations, other researchers can consult not only the results of the sizing procedure but also all the assumptions and the provenance of information. By

publishing these ontologies representing the RPAS with the Linked Data paradigm, users would be able to consult different sources of data and integrate them in their own system. This would be a case of ontologies applied to the Semantic Web, and it can also aid to establish a distributed network of knowledge across different organizations, fostering collaborative environments and cooperation.

As it can be seen, there is outstanding potential in the application of ontologies not only to aeroplane computerised design environments in general, but also to the case of RPAS, attending to their peculiarities. The main tools and ideas that can be used to develop this software environment have been developed within this thesis, but this line of work in itself is an ambitious prospect which was outside the time-frame of the doctoral studies. Nevertheless, it has been included here due to its promising advantages, the tight relationships with the findings and products of the thesis, and the fact that using the results already achieved, it is expected to be tackled in the short-medium term.

12.3. Overall concluding remarks

Finally, upon having commented specific conclusions and future lines of work related to different areas of the thesis, here the final remarks are drawn going back to the initial objectives of the research presented in this thesis.

Within the context of the rapidly growing field of RPAS, it has been seen that new approaches are required to fully leverage the potential of these aircraft. In particular, novel design methodologies considering their particularities are needed, as the differences of RPA when compared to manned aircraft often result in different hypothesis and scope of the required analyses, thereby traditional methods for manned aircraft initial sizing and design might not be applicable in many cases. The needs assessment and literature review conducted at the outset of this work identified that there was a significant gap in methodologies for initial sizing and early design of RPA. Particularly, the latest evolutions of regulations, as well as the multi-role capability of this aircraft, have been absent from most of the previous works, which is why the thesis has focused mainly on those dimensions.

Within the thesis, a combined conceptual design methodology composed of three different approaches has been developed and tested. The overall design method has achieved the main objectives of the thesis regarding the development of design methodologies: it allows for a rapid sizing of a RPA attending to regulatory and multi-role requirements, reaching a level of definition for the aircraft which is adequate for a conceptual design approach within an accuracy according to the requirements for this stage in the product development. Some lines of future work in each of these approaches were commented in section 12.1, but at the moment, it constitutes a functional and

validated approach for the initial sizing of multi-role fixed-wing RPA within the scope of this research.

Aside from this novel conceptual design methodology, which is the main output of the thesis, up-to-date reviews have been conducted focusing on three topics of outstanding interest within the domain of RPAS: regulations, computerised design environments, and Artificial Intelligence (AI) applications. It is clear that these areas, which have great potential within RPA design, are themselves very broad. In the case of the area of regulations, these have been integrated in one of the main three novel approaches developed in the thesis. With respect to the areas of design packages and AI, albeit it was not possible to develop novel approaches in their domains within the scope of this thesis, we expect that the reviews can serve as valuable foundation for future work in this area, having compiled and ordered a great amount of information on the topics of computerised design environments and ontologies. Furthermore, in this thesis, some original perspectives and insights were provided in these areas, particularly in relation to their application to the field of RPA. In fact, some of these proposed guidelines have influenced the design methodologies developed here, for instance by applying the modular approach, and establishing a clear and common definition of the RPA main parameters when developing the database. Therefore, the studies conducted in these areas have greatly enriched the rest of the content of the thesis, and undoubtedly constitute very promising lines of future research which are tightly connected with the topics and main results of this thesis.

It is clear that there is still much to do in research within the field of RPAS. This is not only due to their potential and current growth, but also due to the way in which the domain of RPAS is becoming increasingly intertwined with many other cutting-edge areas of science and engineering. Some examples include AI, autonomy concerns, novel propulsion systems, airspace management and navigation issues, and new materials for manufacturing, amongst many others. Design and operations are becoming increasingly reticulated with these other areas, which can be expected to have a large impact in future research and development of RPAS. Therefore, it can be expected that future research within this field will not only require a solid base of the engineering aspects of aviation design and operations, but also a significant contribution from these other areas, which can in turn allow to reach novel concepts and solutions in the field of design. With all of this, the author expects that the surveys and original results from this work can constitute a promising basis for future research in this area.

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