

# Decision framework for the integration of RPAS in non-segregated airspace

Pérez-Castán, J.A.,\* Gómez Comendador, F.\*, Rodríguez-Sanz, A.\*, Águeda, G.\*, Zambrano, S. and Torrecilla, J.†

\* Universidad Politécnica de Madrid, Plaza Cardenal Cisneros, 28040, Madrid, Spain.

† ISDEFE, Calle Beatriz de Bobadilla, 28040, Madrid, Spain.

Corresponding author: Javier A. Pérez-Castán, [Javier.perez.castan@upm.es](mailto:Javier.perez.castan@upm.es)

## Abstract

The integration of Remotely Piloted Aircraft System (RPAS) in non-segregated airspace is one of the forthcoming challenges in aviation. This paper develops a decision framework to determine the airways where RPAS should fly. The methodology defines three types of indicators: 1) static indicators based on the geometry of the airspace; 2) dynamic indicators based on the air traffic features; and 3) mixed indicators that combine both static and dynamic indicators. These indicators appraise the airspace state basic elements as airways and crossing points. The decision framework seeks to detect which airways and air corridors - specific Flight Levels (FLs) of an airway - can be fully segregated for the use of RPAS, as well as the airways that favour the integration of RPAS but increasing the risk level. The decision framework is applied to the Spanish upper airspace LECMZGZ from FL 250 to 300. Results conclude there are no airways that permit their use as segregated airways. However, two air corridors at FL 270 allow the segregated integration of RPAS. Moreover, the decision framework detects the airways that favour the integration of RPAS although they would have an impact on the risk level.

## Keywords

Air Transport; RPAS; RPAS Integration; Airspace planning; Conflict-risk Assessment; Non-segregated airspace

## 1. Introduction

The integration of Remotely Piloted Aircraft System (RPAS) in non-segregated airspace is one of the challenges that the aviation community must face in the years ahead. According to European RPAS Steering Group [1], the initial integration of RPAS in non-segregated airspace is planned to the time frame 2019-2023. This goal requires a broad and structured analysis of the current situation as well as the potential solutions to be implemented. In this way, the development of a framework to ensure the safe integration of RPAS is crucial for their future.

RPAS operation in airspace does not require higher technological developments but the detailed analysis and subsequent confirmation about its safety. Both European Aviation Safety Agency (EASA) and Federal Aviation Administration (FAA) specifies that RPAS integration must not imply a diminish on safety levels [2], [3]. This means the development of a methodology that bears in mind the operational features of RPAS and permits to set out whether or not it is safe to operate RPAS jointly with conventional aircraft [4]–[6].

Where should RPAS fly in a non-segregated aircraft? This is the question that this paper tries to answer. Currently, the concept of free-route airspace is far from being the general trend in European airspace, although it is already implemented in several airspaces [7]. Then, RPAS must adapt to the present airway network shared with conventional aircraft. In the short-term, the main issue is about the coexistence of both airspace users. RPAS operational features differ from conventional aircraft ones [8], [9]. Moreover, conflict management is a harsh issue because there is no previous knowledge about RPAS operational uncertainty operation [10]. Promoted by this lack of technical, operational and human knowledge about RPAS operation, regulators seek to integrate RPAS towards seeking a minimum interaction with conventional aircraft [11], [12]. This concept underlies the idea that the airspace should be divided into zones. This is a theoretical limit because airspace cannot be completely segregated in a block for RPAS and another one for conventional aircraft. Nonetheless, there exist airways or air corridors – specific Flight Levels (FLs) of an airway – in an airspace that could permit the segregation or favour their use for the integration of RPAS.

Primary assessments about RPAS integration focus on three research lines. The first deals with the global problem of risk management. Clothier et al. [13] developed a framework for structuring the safety case of the RPAS operation. Moreover, various agencies assessed the main difficulties that must be solved before RPAS operation [14], [15]. The second research line analyses the risk imposed by the operation for a single RPAS flight regarding the number of casualties. Different authors developed different risk models to calculate what populated areas present more risk for on-ground pedestrians [16]–[18]. The last research line involves the development and implementation of collision-risk models between RPAS and conventional aircraft. There are assessments about RPAS collision avoidance [9], [19], [20] (similar to conventional aircraft situations) but few of them assess conflict risk [21], [22]. However, none of these studies responds either how the RPAS integration should be or where RPAS could fly in non-segregated airspace.

With the aim of responding to the research question, it is required to analyse the safety level of airspace and to dispose of a specific methodology. Manual 9689 of International Civil Aviation Organization (ICAO) [23] sets out that airspace planning requires a thorough analysis of every factor that can affect safety. In [24], [25], authors claim the need for airspace design fulfilling levels of safety under diverse operational circumstances. Different authors develop different models to assess collision risk based on airspace geometry [26], [27]. A step further, Netjasov [28] develops a conflict-risk model to assess the level of safety regarding air traffic flows. However, these studies could not model the influence of different variables as conflict geometry, density and airway length among others. The issue underlies if we try to evaluate the airspace risk level, crucial information will be missed to understand the operational frame. In addition, there is

not a unique methodology that allows assessing the airspace risk-state and the integration of RPAS.

Therefore, the goal of this research is to respond to where RPAS should fly in non-segregated airspace. The authors develop a new decision framework to detect what airways (or airspace corridors) allow the safe integration of RPAS. The methodology defines several indicators that model the geometrical and operational features of airspace. The indicators sort airways and crossing points to detect airways (or air corridors) where RPAS can be segregated because they do not imply any impact on the risk level. Moreover, the decision framework detects airways that favour the integration of RPAS by imposing a lesser impact on safety. A further aim is to set out the pillars of a future decision-tool for Air Navigation Service Providers.

The rest of the article is structured as follows. Section 2 presents the methodology that underlies the decision framework by defining different types of variables and indicators. The indicators constitute the main outputs of the methodology that permit to assess the viability of the RPAS integration. Section 3 describes the case study. Section 4 presents and discusses the results obtained for the application of the methodology into the case study. Lastly, Section 5 summarises the main contributions and further works.

## 2. Methodology

The goal of this research is to detect which airways and air corridors permit and favour the integration of RPAS. To achieve this aim, we develop a new decision framework based on the characterisation of a set of indicators. These indicators address different objectives depending on the variables that constitute them. One of the innovations of this work is to separate the physical variables of the airspace (airways and crossing angles) from the operational variables of the air traffic. Then, the variables can present a static behaviour (based on the airspace geometry and fix elements) or a dynamic behaviour (based on the operational features of the air traffic).

The scope of this decision framework is ascertained to be applied in the airspace design stage. With this aim, the dynamic variables seek to reference values of air traffic flows (typically for a design day), i.e., we plan a solution for airspace design purposes. Nonetheless, this decision framework goes beyond because it can be applied to specific periods of time. For instance, if the air traffic distribution varies throughout the day, it can be calculated the availability of airways depending on the period of time considered. This time-dependent solution is planned to be solved in future works.

### 2.1. Variables

Different variables underlie the methodology by providing all the information about the airspace design and the operation. Variables are divided into two groups depending on whether they are related to airspace design (static variables) or with air traffic (dynamic variables):

- Static variables are related with the geometry of the airspace: airway ( $i$ ), airway length ( $L_i$ ), crossing angle ( $\alpha_{i,j}$ ), critical section ( $d_{i,j}$ ), flight level ( $s$ ) and crossing point ( $n$ ). These variables are inherent of each airspace and model it.
- Dynamic variables are related to the existing air traffic in the airspace: density of airway ( $Q_i$ ), density of airway per FL ( $Q_i^s$ ), average horizontal speed per airway ( $\bar{v}_i$ ) and average horizontal speed per airway and FL ( $\bar{v}_i^s$ ). These variables are dynamic because they change depending on the period of time selected.

## 2.2. Indicators

The indicators model and characterise the airspace situation. They are key elements to sustain the decision framework. These indicators are divided into three areas depending on the variables that conform them. There are three types of indicators:

- Static indicators provide information of the airspace design state. There are two static indicators that focus on airway complexity ( $\beta$ ) and crossing-point complexity ( $\gamma$ ).
- Dynamic indicators assess the state of the airways and crossing points taking into consideration the air traffic flows. There are two dynamic indicators focusing on the occupancy of airways ( $\delta$ ) and crossing-points ( $\epsilon$ ), and one dynamic indicator that assess the airway availability ( $\zeta$ ).
- Mixed indicators provide information for the risk assessment. They are constituted by a combination of static and dynamic indicators for every airway ( $\eta$ ) and crossing point ( $\theta$ ).

These indicators provide a thorough knowledge of the airspace design, operational situation and risk issues to determine the viability of RPAS integration. Table 1 presents the nomenclature of previous indicators.

**Table 1. Nomenclature of indicators.**

<b>Static indicators</b>	Airway complexity	$\beta$
	Crossing-point complexity	$\gamma$
<b>Dynamic indicators</b>	Airway occupancy	$\delta$
	Crossing-point occupancy	$\epsilon$
	Airway availability	$\zeta$
<b>Mixed indicators</b>	Airway risk	$\eta$
	Crossing-point risk	$\theta$

### 2.2.1. Static Indicators

Static indicators provide the necessary information to assess the current situation of the airspace based on the airspace morphology and geometry. Static indicators focus on airspace design elements: airways and crossing points. Hence, this analysis classifies the airways and crossing point depending on their complexity.

#### *Airway complexity indicator ( $\beta$ )*

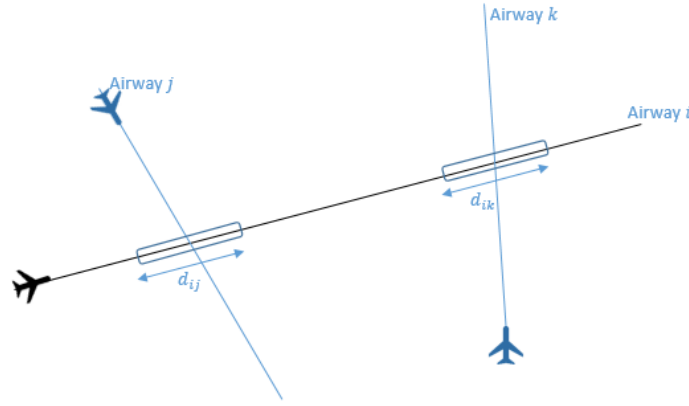
The complexity of an airway is determined by the ratio of the airway which could potentially suffer a conflict with other airways. These sections are called critical sections and are located around a crossing point. The location where at least two airways intersect is a crossing point. Then, a critical section is the area of an airway where an aircraft can suffer a conflict with other aircraft of a different airway [28]. The value of a critical section is calculated based on the crossing angle and the separation minima ( $S_{min}$ ).

$$d_{ij} = \frac{2S_{min}}{\sin \alpha_{ij}} \quad [1]$$

We define airway complexity ( $\beta_i$ ) by the sum of every critical section generated in an airway. This value is obtained by the sum of the length of every critical section. Then, a greater number of crossing points in an airway implies a greater number of critical sections. The airway complexity indicator relates the ratio of an airway that it is exposed to a conflict with respect to the airway length:

$$\beta_i = \frac{\sum_{j \neq i} d_{i,j}}{L_i} \quad [2]$$

Figure 1 shows an instance where two airways ( $j, k$ ) cross airway  $i$ .  $d_{i,j}$  and  $d_{i,k}$  represents the critical sections of the airway  $i$ . Those airways with a greater indicator  $\beta_i$  are the most exposed to a conflict. In the case an RPAS fly through these airways, they will be more exposed to a conflict. Therefore, these airways do not favour the integration of RPAS because they will impose a high increase on the risk level and, possibly, the number of interventions to avoid conflicts.



**Figure 1. Critical sections associated with the airway  $i$ .**

#### *Crossing-point complexity indicator ( $\gamma$ )*

The complexity of a crossing point depends on two factors:

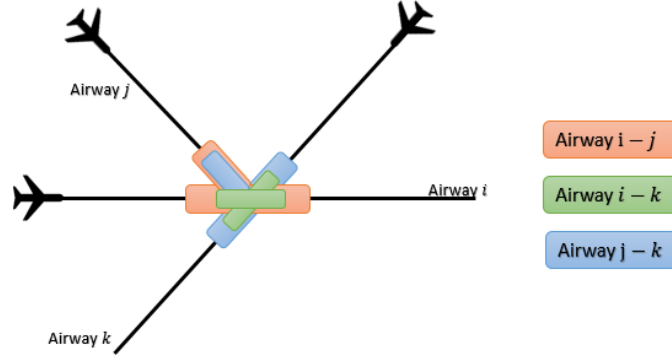
- The number of intersections between airway pairs: the higher the number of airways, the higher the probability of conflict occurrence is.
- The crossing angle constituted by the airways: the lesser the crossing angle, the higher the probability of conflict occurrence is.

Combining both factors, it can be established the complexity of a crossing point ( $\gamma_n$ ) with the following equation:

$$\gamma_n = \frac{\sum_n d_{i,j}}{d_{elem}} \quad [3]$$

Where  $\sum_n d_{i,j}$  is the sum of critical sections at crossing point  $n$  and  $d_{elem}$  is the elemental critical section.  $d_{elem}$  corresponds to the theoretical intersection between two airways with a crossing angle of  $90^\circ$  where there is no airway continuity. We refer to airway continuity as the situation where an aircraft must change of airway because the original airway ends at the crossing point. The critical section associated to  $d_{elem}$  is equal to the horizontal separation minima  $d_{elem} = \frac{S_{min}}{\sin 90^\circ} = S_{min}$ .

Figure 2 shows a crossing point where three airways intersect ( $i, j$  and  $k$ ) and three crossing exist ( $i - j, i - k$  and  $j - k$ ). Each crossing generates a critical section for each airway pair. The length of the critical sections differs among them because the crossing angle is different. The smaller the crossing angle, the bigger the critical section is.



**Figure 2. Critical sections at the crossing point  $n$ .**

### 2.2.2. Dynamic indicators

In the same way, static indicators focus on airspace design, dynamic indicators focus on the operational features of air traffic. The operational features provide information about the aircraft performances within the airspace. Dynamic indicators are related to airways and crossing point in the same way as the static indicators. There are dynamic indicators focused on the airway occupancy ( $\delta$ ) and the crossing-point occupancy ( $\epsilon$ ). Besides, we define the availability indicator ( $\zeta$ ) that detect the possibility of a conflict between air traffic flows. This allow us to organise the operational features of the airspace based on airways and crossing points. Airways and crossing-points with higher occupancy indicators imply high-levels of density, while a null occupancy indicator means that there is no traffic.

Dynamic indicators are calculated for one-hour operation during an operational day. This research focuses on airspace design purposes, i.e., we work with average air traffic flows that model the airspace. However, the decision framework can be developed to deal with a time-dependent function of air traffic flows.

#### *Airway occupancy indicator ( $\delta$ )*

This indicator measures the occupancy rate of the airways with respect to the theoretical maximum. Based on the data provided, it can be extracted the whole number of aircraft in airspace and the airway densities throughout a period of time ( $Q_i$ ). In addition, the average ground speed of the air traffic flow per airway can be extracted ( $\bar{v}_i$ ), as well as the same values for every FL involved. The theoretical maximum density of an airway ( $Q_i^{max}$ ) and the airway occupancy indicators are obtained from the following equations:

$$Q_i^{max} = \frac{\bar{v}_i}{S_{min}} \quad [4]$$

$$\delta_i = \frac{Q_i}{Q_i^{max}} \quad [5]$$

The theoretical maximum density is selected because, currently, the average ground speed of an air traffic flow is similar for every airway (although each aircraft speed can vary). However, the average speed can be modified in the case RPAS are introduced because their operational speeds are lower than conventional aircraft.

#### *Crossing-point occupancy indicator ( $\epsilon$ )*

The number of aircraft that pass through a crossing point determines its occupancy. Hence, the crossing-point occupancy indicator  $\epsilon$  is calculated by the sum of the occupancy indicators of the airways that intersects on it.

$$\varepsilon_n = \sum_{i \in n} \delta_i \quad [6]$$

#### *Airway availability indicator ( $\zeta$ )*

This dynamic indicator ( $\zeta$ ) is a sequel of the crossing-point occupancy indicator because it is based on the same information (indicator  $\delta$ ) but with a different target.  $\zeta$  refers to the airway availability with the finality of assessing the segregation of airways (or air corridors) for the integration of RPAS. This indicator assesses the conflict probability between air traffic flows of two airways that intersect in a crossing point. While the indicator  $\varepsilon$  is a relative meter of the number of aircraft that pass through a crossing point,  $\tau_n$  is the crossing point influence and is calculated by the sum of the products of  $\delta$  indicators per airway pairs.

$$\tau_n = \sum_{\substack{i, j \in n \\ i \neq j}} \delta_i \delta_j \quad [7]$$

Therefore, indicator  $\tau_n$  specifies in which crossing points conflicts can happen. If there is a crossing point where intersect several airways and it only exists traffic in one of them, the availability indicator is null ( $\tau_n = 0$ ). Otherwise, the indicator is greater than zero ( $\tau_n \neq 0$ ). Moreover, an airway is constituted by a set of crossing points. Then, the airway availability indicator  $\zeta_i$  is obtained by the addition of the crossing points influence.

$$\zeta_i = \sum_{n \in i} \tau_n \quad [8]$$

There are two possible results:

- 1)  $\zeta_i = 0$  implies that the airway  $i$  is conflict free.
- 2)  $\zeta_i \neq 0$  implies that the airway  $i$  can suffer conflicts with other airways.

Moreover, the airway availability indicator works also to model a conflict level to contrast the segregation of air traffic per airways (or air corridors). To achieve that, we need to calculate the total conflict value of the airspace ( $\zeta_{tot}$ ) based on the sum of every airway (or air corridor):

$$\zeta_{tot} = \sum \zeta_i \quad [9]$$

#### 2.2.3. Mixed indicator

The mixed indicators provide ensemble information of the airspace from the airways and crossing points. Both indicators (airway and crossing-point risk indicators) are a combination of their respective static and dynamic indicators. Risk indicators provide an initial risk assessment for the integration of RPAS, i.e., they provide a first assessment of the cost regarding safety that can impose the integration of RPAS. These indicators detect the airways that favour the integration of RPAS because the risk impact is reduced.

#### *Airway risk indicator ( $\eta$ )*

The product of airway static and dynamic indicators composes the airway risk indicator. This indicator relates the complexity of an airway with its occupancy rate:

$$\eta_i = \beta_i \delta_i \quad [10]$$

#### *Crossing-point risk indicator ( $\theta$ )*

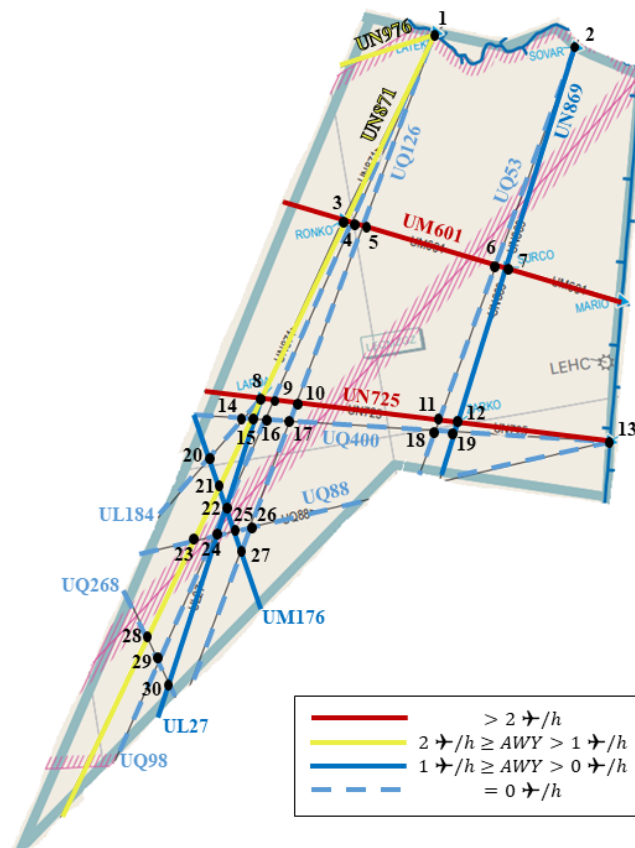
The product of crossing-point static and dynamic indicators composes the crossing-point risk indicator. This indicator relates the complexity of the crossing-point with its occupancy rate:

$$\theta_n = \gamma_n \varepsilon_n \quad [11]$$

Finally, the definition of the above indicators permits to know what airways (or air corridors) permit their segregated use and what airways favour the integration of RPAS in the airspace.

### 3. Case study: LECMZGZ airspace

Once we have described the decision framework, we present the airspace volume selected to validate the methodology. Herein, the airspace LECMZGZ is selected. It is located in the upper airspace of Madrid (Spain). The high number of cruise flights and the scarce interference of the climbing /descending flights are the main contributors. The FLs selected for the integration of RPAS comprehend from FL 250 to FL 300. The reason is that the air traffic flows in these FLs are reduced compared with upper FLs. This fact considerably diminishes the number of potential conflicts and likely facilitate the integration of RPAS without an airspace capacity reduction. This section describes the static and dynamic variables that are necessary for the different indicators.



**Figure 3. Representation of LECMZGZ airspace.**

Figure 3 shows the structure of the LECMZGZ airspace. 14 airways and 30 crossing points build this airspace. Air traffic flows present clear features for the corridor North-South (37.7%) and East-West (39.5%). The percentage of conventional aircraft climbing or descending represent less than 15%, and their influence is discarded in this approach.

Table 2 summarises the main characteristics of the airspace: airway length in Nautical Miles (NM), airway density (aircraft per hour) and average speed (knots) per airway and FL.

**Table 2. Physical and operational characteristics of the airways.**

Airway (i)	$L_i$ (NM)	FL 250		FL 260		FL 270		FL 280		FL 290		FL 300	
		$Q_i$	$\bar{v}_i$	$Q_i$	$\bar{v}_i$	$Q_i$	$\bar{v}_i$	$Q_i$	$\bar{v}_i$	$Q_i$	$\bar{v}_i$	$Q_i$	$\bar{v}_i$
UM601	45.7	0.02	401	0.47	369	0.35	377	0.7	431	0.18	424	0.6	459
UN725	53.3	0.03	411	0	0	0	0	0.03	476	0.09	434	1.71	494
UQ400	54.0	0	0	0	0	0	0	0	0	0	0	0	0
UQ88	47.0	0	0	0	0	0	0	0	0	0	0	0	0
UN976	12.0	0.06	382	0	0	0	0	0	0	0.5	458	0	0
UL184	19.3	0	0	0	0	0	0	0	0	0	0	0	0
UQ268	13.0	0	0	0	0	0	0	0	0	0	0	0	0
UL27	37.5	0.04	372	0.05	408	0	0	0.05	465	0.04	384	0.05	418
UN871	103.5	0	0	0.3	410	0	0	0.21	467	0.07	424	0.15	445
UQ98	97.5	0	0	0	0	0	0	0	0	0	0	0	0
UQ126	87.6	0	0	0	0	0	0	0	0	0	0	0	0
UQ53	60.7	0	0	0	0	0	0	0	0	0	0	0	0
UN869	60.3	0.16	401	0.04	399	0.08	402	0.04	375	0.12	414	0	0
UM176	23.0	0	0	0	0	0.01	415	0	0	0.05	427	0.02	431

As expected, only half of the airways (7 of 14) have air traffic (cells with grey shadow). In addition, air traffic density is extremely reduced, being lower than one aircraft per hour at every FL. This low density in lower FLs sustains the suitability of this volume of airspace for the integration of RPAS. Average ground speed for every FL approaches to 400 knots. The introduction of RPAS (with an average speed of 250 knots) will imply a modification concerning conventional aircraft.

Table 3 presents the crossing angles between airways. The symbol “-” denotes airway pairs that do not intersect in LECMZGZ. Attending to Table 3, the geometry of LECMZGZ airspace presents an advantage because the majority of the crossing points (24 of 30) are only intersected by two airways.

**Table 3. Crossing-point angles between airways in LECMZGZ.**

Airway (i)	Airway (j)													
	$\alpha_{i,j}$	UM601	UN725	UQ400	UQ88	UN976	UL184	UQ268	UL27	UN871	UQ98	UQ126	UQ53	UN869
UM601	-	-	-	-	-	-	-	-	80	82	85	85	88	-
UN725	-	-	4	21	-	57	-	79	71	73	76	76	79	-
UQ400	-	4	-	17	-	53	-	75	68	69	72	72	75	-
UQ88	-	21	17	-	-	-	-	58	51	52	55	-	-	85
UN976	-	-	-	-	-	-	-	-	44	46	49	-	-	-
UL184	-	57	53	-	-	-	-	22	15	-	-	-	-	59
UQ268	-	-	-	-	-	-	-	44	51	50	-	-	-	-
UL27	-	79	75	58	-	22	44	-	7	6	-	-	-	37
UN871	80	71	68	51	44	15	51	7	-	2	5	-	-	44
UQ98	82	73	69	52	46	-	50	6	2	-	3	-	-	43
UQ126	85	76	72	55	49	-	-	-	5	3	-	-	-	40
UQ53	85	76	72	-	-	-	-	-	-	-	-	-	-	-
UN869	88	79	75	-	-	-	-	-	-	-	-	-	3	-
UM176	-	-	-	85	-	59	-	37	44	43	40	-	-	-

Finally, horizontal separation minima in the upper airspace in Spain and Europe is 5 NM [29].

## 4. Results

This section introduces and discusses the results obtained for the decision framework about the integration of RPAS in LECMZGZ airspace. We calculate the static, dynamic and mixed indicators of Section 2 and we present them sorted by the  $\eta$  indicator. In the cases where  $\eta = 0$ , airways with higher  $\beta$  are on the top. Thus, the airways that favour the integration of RPAS are located on the bottom.

Table 4 presents the results of static, dynamic and mixed indicators for airways of LECMZGZ.

**Table 4. Results for the airways of LECMZGZ.**

<b>Aerovia (<i>i</i>)</b>	<b><math>\beta</math></b>	<b><math>\delta</math></b>	<b><math>\zeta</math></b>	<b><math>\eta</math></b>
<b>UN725</b>	1.345	3.24E-02	6.68E-04	4.36E-02
<b>UN871</b>	1.384	1.09E-02	1.06E-03	1.51E-02
<b>UM601</b>	0.534	2.66E-02	4.36E-04	1.42E-02
<b>UN976</b>	0.599	2.24E-02	2.43E-04	1.34E-02
<b>UN869</b>	1.583	5.53E-03	3.26E-04	8.75E-03
<b>UL27</b>	1.630	3.17E-03	5.26E-04	5.17E-03
<b>UM176</b>	1.101	7.50E-04	1.05E-05	8.30E-04
<b>UQ53</b>	1.573	0	0	0
<b>UQ268</b>	1.510	0	0	0
<b>UQ98</b>	1.469	0	0	0
<b>UQ400</b>	1.328	0	0	0
<b>UQ126</b>	1.090	0	0	0
<b>UL184</b>	1.001	0	0	0
<b>UQ88</b>	0.590	0	0	0

Table 5 presents the results of static, dynamic and mixed indicators for crossing points of LECMZGZ. In this case, the crossing-point identification number sorts results.

**Table 5. Results for the crossing-points of LECMZGZ.**

<b><math>n</math></b>	<b><math>\gamma</math></b>	<b><math>\varepsilon</math></b>	<b><math>\tau</math></b>	<b><math>\theta</math></b>
<b>1</b>	77.851	3.33E-02	2.43E-04	2.589
<b>2</b>	38.185	5.53E-03	0	0.211
<b>3</b>	4.062	3.74E-02	2.89E-04	0.152
<b>4</b>	4.039	2.66E-02	0	0.107
<b>5</b>	4.015	2.66E-02	0	0.107
<b>6</b>	4.015	2.66E-02	0	0.107
<b>7</b>	4.002	3.21E-02	1.47E-04	0.129
<b>8</b>	42.927	4.4E-02	4.89E-04	1.993
<b>9</b>	4.183	3.24E-02	0	0.136
<b>10</b>	4.122	3.24E-02	0	0.136
<b>11</b>	4.122	3.24E-02	0	0.136
<b>12</b>	4.075	3.79E-02	1.79E-04	0.155
<b>13</b>	32.097	3.24E-02	0	1.039
<b>14</b>	5.009	0	0	0
<b>15</b>	34.972	1.40E-02	3.45E-05	0.491
<b>16</b>	4.285	0	0	0
<b>17</b>	4.206	0	0	0
<b>18</b>	4.206	0	0	0
<b>19</b>	4.141	5.53E-03	0	0.023
<b>20</b>	4.667	7.50E-04	0	0.004
<b>21</b>	5.758	1.16E-02	8.15E-06	0.067
<b>22</b>	41.597	3.92E-03	2.38E-06	0.163
<b>23</b>	5.147	1.09E-02	0	0.056
<b>24</b>	40.812	3.17E-03	0	0.129
<b>25</b>	4.015	7.50E-04	0	0.003
<b>26</b>	4.883	0	0	0
<b>27</b>	6.223	7.50E-04	0	0.005
<b>28</b>	5.147	1.09E-02	0	0.056
<b>29</b>	5.221	0	0	0
<b>30</b>	5.758	3.17E-03	0	0.018
<b>Total</b>	-	-	<b>1.39E-03</b>	-

Figure 4 summarises the main results regarding operational indicators. Airways without air traffic ( $\delta = 0$ ) are represented by dashed lines and crossing-points without conflict probability ( $\tau_n = 0$ ) are rounded by dashed circles.

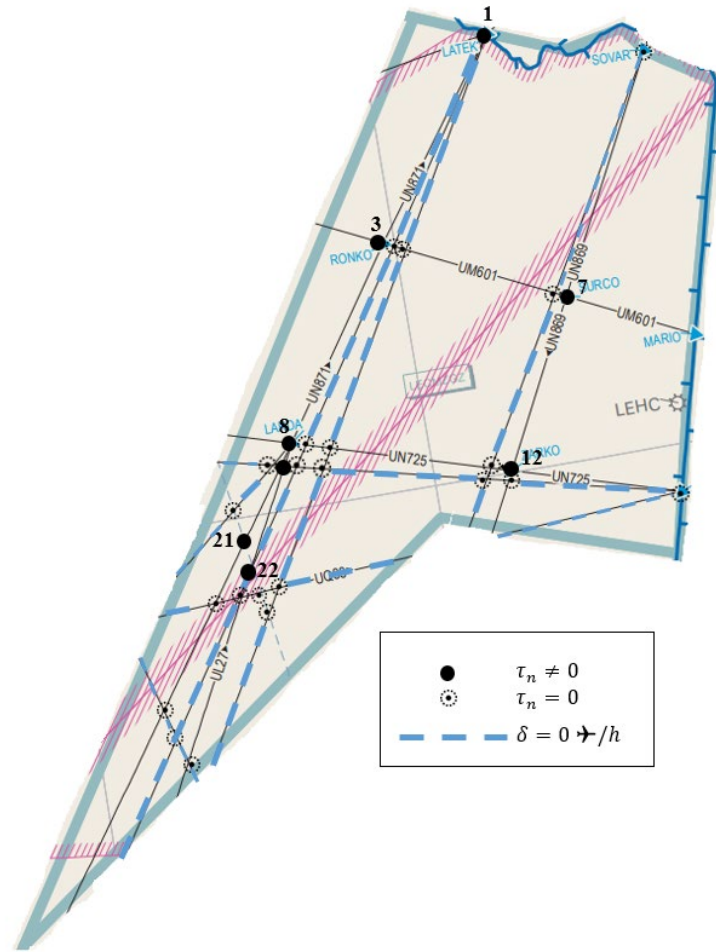


Figure 4. Representation of dynamic indicators at LECMZGZ.

#### 4.1. Static indicators

$\beta$  indicator represents the ratio between airway length where a conflict can occur and the airway length, i.e., which is the ratio of the airway that an aircraft is operating in a critical section. Variables that conform the indicator  $\beta$  are the number of crossing points and the crossing angle with the rest of airways. Table 4 provides the values:

- Airway UL27 has the highest value ( $\beta_{UL27} = 1.630$ ). It is an airway with  $L_{UL27} = 42.8$  NM and two crossing points with extremely reduced crossing angles ( $7^\circ$  and  $6^\circ$ ).
- The following highest values correspond to the airway UQ53 ( $\beta_{UQ53} = 1.573$ ) and UN869 ( $\beta_{UN869} = 1.573$ ). Both airways are larger (60.4NM and 60.1NM) and are composed by three crossing points. The reason of a high  $\beta$  is due to the existence of the lowest crossing angle ( $3^\circ$ ).
- Three above values are greater than 1. This implies that the sum of the critical sections exceeds the length of the airways. Every aircraft that fly these airways are potentially in risk of suffering a separation minima infringement. Therefore, an RPAS should avoid those airways.
- The lowest value is obtained for airway UM601 ( $\beta_{UM601} = 0.534$ ), which length is 45.7 NM. This airway is composed by five crossing points. However, all of them have a crossing angle of roughly  $90^\circ$ .

These results conclude that the number of crossing points in an airway is not the crucial factor but the crossing angle.

$\gamma$  indicator represents the complexity associated to each crossing point. This is obtained by the sum of the different critical sections of the airways that concurs on it. If we observe the crossing points 2 and 3 (Table 5) that present the same number of airways, it can be detected a great difference of  $\gamma$  ( $\Delta\gamma = 34.1$ ). This fact reinforces the previous conclusion: the crossing angles are the most important factors for the complexity indicator. A small angle influences more the static indicators than the number of airways.

## 4.2. Dynamic Indicators

$\delta$  indicator represents the occupancy of an airway compared with the theoretical maximum density that can be operated. Airways with greater  $\delta$  (Table 4) are more occupied – such as UN725 ( $\delta_{UN725} = 3.24E - 02$ ), UM601 ( $\delta_{UM601} = 2.66E - 02$ ) and UN976 ( $\delta_{UN976} = 2.24E - 02$ ). Although these airways are the busiest of the airspace, the occupancy rate is very low because barely fly 3% of their maximum flow. Typical values of airway occupancy rate round about 10-15% in the upper airspace. On the other hand, there are 7 airways without air traffic flow ( $\delta = 0$ ). A variable that influences this indicator is the average ground speed of the air traffic flows; the greater the ground speed, the greater the maximum theoretical density and, therefore,  $\delta$  is reduced. However, every airway of this airspace presents similar average ground speed. Then, the average ground speed is not a crucial factor.

$\varepsilon$  indicator refers to the occupancy of a crossing point. This indicator is directly related with the airway occupancy indicator ( $\delta$ ).  $\varepsilon$  indicator is higher when the airways that intersect in it are busier. Crossing point 8 is the densest crossing point of the airspace ( $\varepsilon_8 = 4,64E - 02$ ). It is constituted by four airways: UN725, UL184, UL27 and UN871. However, the occupancy rate is very low due to the low density of the airways. On the other hand, there are only six crossing points without any traffic ( $\varepsilon = 0$ ).

### 4.2.1. Airway availability indicator

This section presents the results obtained for the indicator  $\zeta$  divided into two sections: airway segregation and air corridor segregation. We introduce the results separated because it facilitates to understand the implications of this indicator.

#### *Airway segregation*

$\zeta$  indicators assesses the possibility of conflict occurrence in an airway. This indicator is a precursor of a more complex indicator of conflict probability. The goal is to detect which airways can be selected for a segregated use with RPAS.

The first step is to calculate the indicator  $\tau_n$  for every crossing point. The crossing points with  $\tau_n = 0$  implies that there is no possibility of conflict occurrence. The reason is that a conflict implies the situation of at least two airways with air traffic flows. LECMZGZ airspace only presents 8 crossing points with  $\tau_n \neq 0$ . 22 crossing points do not present conflict occurrence ( $\tau_n = 0$ ). This result implies that interventions to avoid conflicts are only located at 26.7% of the crossing points. In addition, the crossing point with higher  $\tau$  is the crossing point 8. This result coincides with the indicator  $\varepsilon$ .

The second step is to calculate the indicator  $\zeta_i$  for every airway. Similar to  $\tau_n$ , airways with  $\zeta_i = 0$  cannot have a conflict with other air traffic flows under above operational features. In this airspace, the airways with air traffic (50%) present conflict probability while airways without air traffic do not. This is one of the features of this airspace because most of the crossing points are constituted by two airways. Then, the integration of RPAS by segregated airways can be carried out on 7 airways.

Finally, we calculate the limit associated with the whole airspace.  $\zeta_{tot}$  is calculated by the sum of all  $\zeta_i$  indicators. This value permits to calculate the viability of airway segregation for RPAS. As

commented previously, the goal of this indicator is to calculate what airways can integrate RPAS without an increase of conflict probability. To achieve this, we introduce RPAS in the airways that currently do not present air traffic ( $\delta = 0 \rightarrow \delta = 1$ ) and we recalculate the value of  $\zeta_{tot}$ . The result is denoted by  $\zeta_{lim}$ . The airways that do not suppose an increment on the conflict level ( $\zeta_{lim} < \zeta_{tot} = 1.39E - 03$ ) permit their segregated use for RPAS.

**Table 6. Analysis of  $\zeta_{total}$  for the segregation of airways.**

Airway ( <i>i</i> )	$\zeta_{lim}$
UQ400	0.053
UQ88	0.048
UL184	0.048
UQ268	0.015
UQ98	0.101
UQ126	0.094
UQ53	0.066

As can be observed in Table 6, the values of  $\zeta_{lim}$  are increased by a factor of 10 when we introduce new RPAS traffic flows in the empty airways. Therefore, there are no airways under these operational conditions that permit the integration of RPAS without increasing the conflict levels, i.e., it is not achievable the segregation of airways for their use with RPAS. This result could have been expected. If there are airways neither with air traffic nor interactions with other air traffic flows, they will no longer be able for air traffic use. However, the occupancy of these airways varies with the vertical profile, i.e., the busiest FLs are the highest FLs. Then, it could be feasible to find air corridors whose segregation for RPAS could be achievable.

#### *Air corridor segregation*

As obtained in the previous section, the air traffic distributions in the airways of LECMZGZ prevent their use from RPAS segregation. However, it does not imply any existence of air corridors that could permit more restricted segregation. This analysis follows the same process developed previously but for each FL. This is a more complex and detailed analysis.

Table 7 presents the results obtained by the integration of RPAS for each FL. Cells filled with “-” refers to those air corridors that have initially conventional aircraft. Cells filled with grey shadow highlight the air corridors that permit their segregation for RPAS. The last row  $\zeta_{tot}(FL)$  provides the limit value of the whole airspace obtained for each FL without RPAS.

**Table 7. Analysis of  $\zeta_{tot}$  for air corridor segregation.**

Airway ( <i>i</i> )	$\zeta_{lim}$					
	FL 250	FL 260	FL 270	FL 280	FL 290	FL 300
UM601	-	-	-	-	-	-
UN725	-	-	-	-	-	-
UQ400	3.9E-03	6.1E-03	1,20E-03	5.1E-03	5.9E-03	3.0E-02
UQ88	1.5E-03	5.9E-03	5,40E-04	4.5E-03	4.8E-03	3.0E-02
UN976	-	4.8E-03	2,96E-06	3.3E-03	-	2.4E-03
UL184	1.5E-03	5.9E-03	5,40E-04	4.5E-03	4.8E-03	3.0E-02
UQ268	5.0E-04	5.4E-03	2,96E-06	4.0E-03	1.0E-03	3.3E-03
UL27	-	-	5,40E-04	-	-	-
UN871	3.0E-03	-	4,30E-03	-	-	-
UQ98	3.0E-03	1.1E-02	4,30E-03	1.2E-02	1.33E-02	3.9E-02
UQ126	2.0E-03	1.0E-02	4,30E-03	1.1E-02	1.23E-02	3.7E-02
UQ53	3.7E-03	5.4E-03	4,90E-03	8.0E-03	6.8E-03	3.5E-03
UN869	-	-	-	-	-	3.5E-03
UM176	5.0E-04	5.4E-03	-	4.0E-03	-	-
$\zeta_{tot}(FL)$	3.7E-06	3.3E-05	3.0E-6	3.4E-05	1.7E-05	1.1E-04



- The application of the methodology to the LECMZGZ sector from FL 250 to FL 300 does not detect any airway for a segregated use. However, we have detected air corridors for this segregated operation. Particularly, airways UN976 and UQ268 at FL 270 allows integration of RPAS during the segregation of these air corridors. The reason is there are no other air traffic flows that can imply a conflict, i.e., the integration of RPAS in these air corridors do not have an impact on conflict probability. However, these results do not provide valuable operational information. These two airways present a secondary behaviour within the airspace design because they do not belong to the primary core airways North-South or East-West.
- The risk indicator provides a relation of the airways and crossing points regarding risk level. According to this indicator, there is only one airway without air traffic that favour the integration of RPAS: UQ88. Particularly, the airways UM601 and UN976 could favour the integration of RPAS. However, they currently have air traffic, and this methodology cannot assess the possibility of RPAS flying jointly with conventional aircraft.

Although these results validate the novel decision framework developed in this paper, it is necessary to deepen the analysis of the airspace due to the scarcity of airways and air corridors available for RPAS. On the one hand, the decision framework deal with airspace design purposes. Nonetheless, in the case we consider time-dependent air traffic flows, the methodology will provide different airways and air corridors as a function of the schedule. This will enhance what airways and air corridors are free depending on the time span. Moreover, this study requires to plan how the integration of RPAS jointly with conventional aircraft in the same airways affect the airspace. On the other hand, this assessment requires the simulation of schedules to compare the operational impact regarding safety. This implies to provide the time span where RPAS should operate and under which circumstances. Finally, the last goal of this research must be to develop a tool that will support regulators to determine the viability of the operation of specific flight plans within specific time spans.

## 5. Conclusions

This paper introduces a novel decision framework to detect where RPAS should fly in non-segregated airspaces. To achieve this goal, the methodology defines several indicators based on the different aspects of airspace design and air traffic flows. Static indicators are based on the airspace complexity, dynamic indicators are based on operational characteristics, and both previous indicators compose the mixed indicators. The methodology consists of ordering the airways and crossing points that constitutes airspace regarding the above indicators. This permit to know which airways and crossing points are the most complex (static indicators), the most occupied (dynamic indicators) and the riskiest (mixed indicators). Moreover, a dynamic indicator provides the airways (or air corridors) where RPAS can operate without an increment on conflict level, i.e., it provides the airways that permit their segregation for the integration of RPAS.

This research is applied to the Spanish upper airspace LECMZGZ from FL 250 to 300. Results conclude that there are no airways in this airspace that permit their segregation for RPAS operation. However, there are two air corridors at FL 270 that permit the integration of RPAS without increasing the conflict level. Moreover, we have detected the airways that favour the integration of RPAS, but an impact on risk level cannot be avoided. Nonetheless, further work must focus on the implementation of temporary restrictions on RPAS operations. This implies to provide the time span where RPAS should operate and under which circumstances. Both regulations (geographical and temporal) will be the basis for the future RPAS operation in non-segregated airspace.

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