UNIVERSIDAD POLITÉCNICA DE MADRID
Escuela Técnica Superior de Ingenieros de Caminos, Canales y Puertos

Development of sustainable ports through the Blue Economy and the use of emerging technology tool

DOCTORAL THESIS

Submitted for the degree of Doctor by:

Javier Vaca Cabrero
Ingeniero de Caminos, Canales y Puertos

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Doctoral Degree in Civil Engineering Systems

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Under the supervision of:
Dr. Alberto Camarero Orive

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A mi hermana Andrea

y a mis padres Fernando y Mercedes

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Abstract

This doctoral thesis examines port sustainability through the integration of the principles of the Blue Economy and emerging technologies, focusing on Spanish ports as strategic nodes in the global logistics chain and as drivers of economic, social, and environmental development. In a context characterized by challenges such as climate change, energy transition, and the need for logistical efficiency, ports play a crucial role in implementing disruptive solutions that foster sustainable development.

The general objective of this research is to analyse the implementation and advancement of port sustainability through the Blue Economy and emerging technologies in Spanish ports. Specifically, the thesis focuses on examining the degree of implementation of established and emerging sectors of the Blue Economy, such as maritime transport and marine renewable energies, as well as exploring the impact of disruptive technologies, including digital universes and digitalization tools, in improving informed decision-making in Spanish ports from a comprehensive perspective.

The adopted methodology combines a mixed qualitative and quantitative approach, integrating tools such as the Delphi method, affinity diagrams, and Bayesian networks. These techniques capture both the objective and subjective dimensions of the phenomenon under study, enabling a comprehensive analysis of the economic, social, and environmental dynamics in ports.

The main findings of the research reveal significant disparities in the implementation of Blue Economy sectors among the 28 Port Authorities in Spain. Established sectors exhibit higher levels of development compared to emerging sectors, which still face barriers related to insufficient investment and technological interoperability. Furthermore, while port digitalization shows notable progress, it also presents significant challenges in terms of standardization, cybersecurity, and collaborative governance.

Regarding practical applications, the research demonstrates how tools such as digital twins and the metaverse can optimize logistical processes, improve strategic planning, and strengthen environmental sustainability. Additionally, the analysis based on Bayesian networks highlights the importance of key indicators, such as environmental investments, to prioritize strategies that maximize positive impacts on sustainability and development.

In conclusion, this thesis emphasizes that the integration of Blue Economy principles and emerging technologies not only contributes to achieving the Sustainable Development Goals but also positions the Spanish port system as a global benchmark for sustainability. The research recommends the implementation of collaborative strategies among port authorities, the private sector, and local communities, fostering a sustainable economic model. Moreover, it underscores the importance of strengthening digital governance and adopting international standards to ensure interoperability and transparency in port operations.

Ultimately, this thesis provides an integral and replicable methodological framework that can be applied to other international contexts, contributing to the development of more sustainable, resilient, and competitive ports within the framework of the 21st-century global economy. The combination of sustainability and emerging technologies represents a unique opportunity to transform the port system into a strategic pillar for sustainable development and energy transition.

Resumen

La presente tesis doctoral analiza la sostenibilidad portuaria desde la perspectiva de la integración de los principios de la Economía Azul y las tecnologías emergentes, centrándose en los puertos españoles como nodos estratégicos en la cadena logística global y motores de desarrollo económico, social y ambiental. En un contexto caracterizado por desafíos como el cambio climático, la transición energética y la necesidad de eficiencia logística, los puertos desempeñan un papel clave en la implementación de soluciones disruptivas que fomenten un desarrollo sostenible.

El objetivo general de la investigación es analizar la implantación y desarrollo de la sostenibilidad portuaria a través de la Economía Azul y las tecnologías emergentes en los puertos españoles. En particular, la tesis se centra en analizar el grado de implementación de sectores establecidos y emergentes de la Economía Azul, como el transporte marítimo o las energías renovables marinas, así como en explorar el impacto de tecnologías disruptivas, como los universos digitales y herramientas de digitalización, en la mejora de la toma de decisiones informada de los puertos españoles desde un enfoque integral.

La metodología adoptada combina un enfoque mixto cualitativo y cuantitativo, integrando herramientas como el método Delphi, los diagramas de afinidad y las redes bayesianas. Estas técnicas permiten captar tanto las dimensiones objetivas como las subjetivas del fenómeno estudiado, facilitando un análisis integral de las dinámicas económicas, sociales y ambientales en los puertos.

Los principales hallazgos de la investigación revelan disparidades significativas en la implementación de los sectores de la Economía Azul entre las 28 Autoridades Portuarias de España. Los sectores establecidos presentan un mayor desarrollo en comparación con los sectores emergentes, estos aún enfrentan barreras relacionadas con la falta de inversión o la interoperabilidad tecnológica. Asimismo, la digitalización portuaria, aunque muestra avances notables, evidencia retos importantes en términos de estandarización, ciberseguridad y gobernanza colaborativa.

En cuanto a las aplicaciones prácticas, la investigación demuestra cómo herramientas como los gemelos digitales y el metaverso pueden optimizar procesos logísticos, mejorar la planificación estratégica y fortalecer la sostenibilidad ambiental. Asimismo, el análisis basado en redes bayesianas destaca la relevancia

de indicadores clave, como las inversiones medioambientales, para priorizar estrategias que maximicen el impacto positivo en términos de sostenibilidad y desarrollo.

En conclusión, esta tesis subraya que la integración de los principios de la Economía Azul y las tecnologías emergentes no solo contribuye al cumplimiento de los Objetivos de Desarrollo Sostenible, sino que también posiciona al sistema portuario español como un referente global en sostenibilidad. La investigación recomienda la implementación de estrategias colaborativas entre autoridades portuarias, sector privado y comunidades locales, promoviendo un modelo económico sostenible. Además, se resalta la importancia de fortalecer la gobernanza digital y la adopción de estándares internacionales para garantizar la interoperabilidad y la transparencia en las operaciones portuarias.

En definitiva, esta tesis ofrece un marco metodológico integral y replicable que puede ser aplicado a otros contextos internacionales, contribuyendo al desarrollo de puertos más sostenibles, resilientes y competitivos en el marco de la economía global del siglo XXI. La combinación de sostenibilidad y tecnologías emergentes representa una oportunidad única para transformar el sistema portuario en un pilar estratégico del desarrollo sostenible y la transición energética.

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Abbreviations and Acronyms

UPM	Universidad Politécnica de Madrid
IoT	Internet of Things
AI	Artificial Intelligence
BE	Blue Economy
EU	European Union
RQ	Research Questions
ETS	Emissions Trading System
SDG	Sustainable Development Goals
PaaS	Port as a Service
MaaS	Mobility as a service
UN	United Nations
EU	European Union
GVA	gross value added
AR	Augmented Reality
PCS	Port Community System
PERS	Port Environmental Review System
BN	Bayesian networks
ICT	Information and Communication Technologies
PPP	Public-Private Partnership
MITMA	Ministerio de Transportes, Movilidad y Agenda Urbana
EDI	Electronic data interchange
TOS	Terminal Operator system
EDIFACT	Electronic Data Interchange for Administration, Trade and Transport.

RFID	Radio Frequency Identification
GPS	geographic position system
MR	Mixed Reality
NFTs	Non-Fungible Tokens
DCS	Distributed Control System
TMS	Transportation Management System
UGC	User Generated Content
5G	Fifth Generation Mobile Network
EEA	European Economic Area
CO_2	Carbon Dioxide
MRV	Monitoring, Reporting, and Verification
IMO	International Maritime Organization
ECA	Emission Control Area
GT	Gross Tonnage
LNG	Liquefied Natural Gas
AFIR	Alternative Fuels Infrastructure Regulation
SSS	Short Sea Shipping
CH_4	Methane
NOx	Nitrogen Oxides
NM	Nautical Miles
POEM	Maritime Spatial Planning Plans
Pgmpy	Python library for Probabilistic Graphical Models

PART I: THEORETICAL FRAMEWORK

1. INTRODUCTION

Chapter 1 introduces the context of the research, highlighting the relevance of port sustainability in Spain through three key axes: sustainable development, the Blue Economy and emerging technologies. It analyses how the Strategic Framework of the Spanish Port System promotes economic, environmental and social sustainability, and how the Blue Economy promotes an efficient use of marine resources. In addition, the role of digitalisation and technologies such as IoT, AI and digital twins in improving port efficiency and sustainability is examined. The chapter closes with the definition of the objectives of the thesis and its methodological structure.

1.1. Background

1.1.1. Sustainable development

Three-dimensional sustainability, which encompasses the economic, environmental and social dimensions, is positioned as a central axis in contemporary port management [1]. In Spain, where ports channel 80% of imports and 60% of exports, their role as backbone of sustainable development is crucial. This approach, aligned with the objectives defined in the 2022 Strategic Framework of the Spanish Port System [2], seeks to transform ports into sustainable, resilient and innovative nodes by 2030.

From an economic perspective, the goal is to optimize logistics operations through advanced technologies such as digital twins, IoT, and automation, while fostering business models based on the circular economy. These initiatives, promoted by strategic lines such as Line 7: Digital Port Administration. Smart and synchronous ports not only reduce operating costs and carbon emissions but also strengthen the competitiveness of Spanish ports in the global context. This framework promotes the comprehensive digitalisation and hyperconnection of port processes, facilitating the transition to a more agile and sustainable model [3].

In the environmental field, port sustainability focuses on minimising the impact of activities on marine and coastal ecosystems. European policies such as the Green Deal and the Fit for 55 programme establish ambitious regulatory frameworks to achieve carbon neutrality for the continent by 2050, objectives aligned with Line 10: Environmentally sustainable ports of the strategic framework. Ports have adopted measures such as the electrification of infrastructure, efficient waste management and the use of renewable energies. In addition, advanced environmental monitoring systems make it possible to assess the impact of port operations in real time, facilitating the mitigation of the effects of climate change and improving resilience to extreme events [4], [5].

The social dimension complements this approach by prioritising inclusive job creation, improving working conditions and fostering social cohesion in port communities. Line 16: Expansion and continuous improvement of human capital underlines the importance of preparing port workers to face the challenges posed by digitalisation and sustainability, promoting inclusive policies and continuous training programmes in emerging skills. Ports, in addition to being economic engines, are spaces for social and cultural interaction. Community participation in strategic decisions is therefore essential to ensure balanced development and wider acceptance of projects [6].

Cases such as the Port of Vigo, with its "Blue Growth" strategy, and the Port of Barcelona, with its "Blue-Up" initiative, reflect how local strategies can be aligned with the guidelines of the Strategic Framework [7], [8]. These experiences demonstrate that the integration of sustainability, emerging technologies and community collaboration is not only possible, but also essential for the success of ports in a context of economic and environmental transition. Overall, the Strategic Framework is consolidated as a transformative tool that, aligned with the principles of three-dimensional sustainability, positions Spanish ports as global benchmarks in sustainability and technological innovation.

1.1.2. Blue Economy

The Blue Economy has established itself as a transformative economic model, differentiated from the Green Economy by its regenerative and circular approach. While the Green Economy has depended on greater investments whose costs fall on consumers, the Blue Economy, according to Pauli (2010) [9], seeks to guarantee the balance of ecosystems through the regeneration and efficient use of resources. This model proposes that waste, instead of being eliminated, becomes inputs for new production processes, following the principle of natural cycles where there is no waste. By adopting this approach, the Blue Economy not only promotes sustainable practices, but also seeks to meet the basic needs of the global population, fostering the well-being of the planet and its inhabitants.

Officially recognised during the United Nations Conference on Sustainable Development in 2012, the Blue Economy has evolved into a cross-cutting model that integrates traditional sectors such as fisheries and maritime transport with emerging areas such as marine renewable energy, biotechnology and the circular economy. This transformation has been embraced by global organizations such as the United Nations, the European Union, and the World Bank, which have included this approach in their sustainable development agendas. In Europe, Blue Growth is a key initiative that promotes the sustainable development of maritime sectors through financing policies and programmes, such as the Recovery and Resilience Fund, with the aim of fostering the green transition and innovation [10], [11], [12].

The Blue Economy is made up of established and emerging sectors, allowing for a more detailed analysis of their economic, social and environmental impact. Among the sectors established are living marine resources, inert maritime resources, marine renewable energies, port activities, shipbuilding and repair, maritime transport and coastal tourism. Together, these sectors generated a gross value added (GVA) of €176.1 billion in 2018, an increase of 15% compared to 2009. In terms of employment, established sectors generated 4.5 million jobs, with significant growth in areas such as coastal tourism and marine renewables, which saw an increase of 20% and 22 times more workers, respectively, since 2009 [10], [13].

On the other hand, emerging sectors represent dynamic and innovative areas within the Blue Economy, highlighting ocean energy, marine biotechnology, desalination, maritime mining, maritime security and surveillance, research and education, and infrastructure [14]. These sectors focus on advanced technological solutions, such as offshore hydrogen generation, the development of biomaterials and biofuels, and the design of sustainable infrastructures that foster the regeneration of marine ecosystems. Although they face challenges in terms of assessment and regulation due to data gaps, their potential contribution to environmental sustainability and economic development is indisputable [15].

Spain plays a leading role in the European Union's Blue Economy, leading key sectors such as coastal tourism, living marine resources and port activities. With a gross value added of more than 33,000 million euros and more than 900,000 jobs generated, the country is consolidating itself as a key player in the promotion of sustainable and innovative practices. Initiatives such as the strategies of the port of Vigo, aimed at reducing emissions and the use of renewable energies, reflect Spain's commitment to European sustainability objectives [16].

Financing and policies are key elements for the success of the Blue Economy. Programs such as the BlueInvest Fund and the Recovery and Resilience Fund have allocated significant resources for innovative and sustainable projects, promoting collaboration between the public and private sectors. These initiatives seek to ensure that the benefits of the Blue Economy are equitably distributed, while fostering the resilience of marine ecosystems and economic growth [10].

In conclusion, the Blue Economy represents a comprehensive model that combines sustainability and innovation to address the environmental and economic challenges of the 21st century. Spain, as a leader in this field, has a unique opportunity to consolidate its position through policies that promote international cooperation and the adoption of emerging technologies, guaranteeing equitable and sustainable development for future generations.

1.1.3. Emerging technologies

The digital transformation in the port sector represents a fundamental change in the management and organization of logistics operations, with the aim of optimizing efficiency, promoting sustainability and improving resilience in the face of global challenges [3]. Ports, which once operated as transit points, have evolved into complex smart logistics ecosystems thanks to the implementation of emerging technologies such as the Internet of Things (IoT), Artificial Intelligence (AI) and Blockchain [17]. These tools allow data to be managed in real time, facilitating informed decision-making and improving operational sustainability. For example, technologies such as digital twins and the metaverse have revolutionized port planning and operation through simulations, predictive analytics, and collaborations in virtual environments.

Digital governance has been key to this transformation, enabling comprehensive coordination of port operations through platforms that centralize data from multiple sources. This strategy has led to the development of "smart ports", where advanced technologies are integrated with physical infrastructures to anticipate problems, optimize logistics processes and ensure environmental sustainability [18]. A notable example is the electrification of docks and the use of renewable energies, measures that significantly reduce carbon emissions and position European ports as leaders in the green transition [5].

Digital twins are one of the most prominent emerging technologies in port digitalisation. These virtual replicas of physical infrastructures allow operational scenarios to be simulated in real time, improving strategic planning and emergency response [19]. In addition, they optimize logistics routes and monitor the structural health of infrastructures, reducing operating costs and promoting sustainability. In parallel, the metaverse, as a shared virtual space, allows actors in the logistics chain to collaborate in real time, conduct training, and evaluate strategic decisions without disrupting real operations [20].

Other emerging tools include blockchain, which ensures transparency and security in logistics transactions; IoT, which collects real-time data on infrastructure and maritime traffic; and AI, which analyses large volumes of data to identify patterns and propose efficient solutions. Also, autonomous vehicles are transforming the loading and unloading of goods, improving safety and reducing operation times [21], [22].

However, the implementation of these technologies faces challenges such as interoperability between systems, cybersecurity, and resistance to organizational change. Overcoming these obstacles requires strong digital governance, the training of specialized personnel, and a constant commitment to technological innovation. As ports advance in their digitalization, they have the potential to become global benchmarks for sustainability and innovation, leading the transition to a more efficient and interconnected future.

1.2. Objectives

1.2.1. General Objective

In a global context marked by the need to move towards sustainable and resilient economic models, ports have emerged as key actors to lead the transition to sustainability. These logistics hubs, which account for 80% of international trade by volume, are not only critical points of connection in global supply chains but also represent unique opportunities to implement innovative practices that integrate sustainability, digitalization and economic efficiency.

The Blue Economy model, with its regenerative and circular approach, offers a transformative framework for maximizing the potential of marine and coastal resources, while emerging technologies, such as digitalization, digital twins, and artificial intelligence, are redefining the way port operations are managed. This landscape raises the need to explore how both approaches can converge to ensure that ports not only respond to current demands but also position themselves as catalysts for sustainable development and innovation.

In this sense, the general objective of this thesis is **to analyse the implementation and development of port sustainability through the Blue Economy and emerging technologies in Spanish ports**. This research seeks not only to provide a comprehensive understanding of the current state of port sustainability in Spain, but also to develop strategic proposals that allow ports to lead the transition towards a more balanced and responsible economic model.

1.2.2. Specific objectives

After defining the general objective of the research, a series of specific objectives are derived that allow us to address the Research Questions (RQ) raised in this study. These specific objectives are strategically linked to the different RQs, providing a structured framework to achieve the expected results.

The following Table 1.1 presents in a schematic way the relationship between the research questions and the specific associated objectives, facilitating a comprehensive and coherent vision of the methodological approach. This organization allows for a clear identification of how each question is addressed through specific objectives, contributing to a systematic and rigorous analysis.

In point 2.5 of the dissertation, these objectives are developed in greater depth, exposing their context, relevance and implementation methodology. This expanded section provides a detailed overview of how each objective is articulated within the different dimensions of the research, aligning with the principles of the Blue Economy, digitalization and sustainability in Spanish ports.

Table 1.1: Specific objectives of the research and secondary objectives derived from it.

Research Question	Specific Objectives	Secondary Objectives
RQ1: What is the degree of implementation of the Blue Economy sectors in Spanish ports and how does it vary between the different port authorities?	To develop a model that assesses the degree of implementation of the Blue Economy sectors in Spanish ports.	1. Design a robust methodological model to evaluate the development of Blue Economy sectors. 2. Identify disparities between ports. 3. Assess the impact of established and emerging sectors. 4. Propose strategies to improve implementation.
RQ2: How can digital technologies transform the operations and sustainability of Spanish ports in a global logistics environment?	Identify and analyse the key factors driving digital transformation in the Spanish port system.	1. To assess the current state of digitalisation in ports. 2. Propose a strategic framework for digital governance. 3. Analyze challenges and opportunities of digitalization. 4. Promote the integration of sustainability into digital processes. 5. Develop indicators to measure impact.
RQ3: How can virtual universes transform the operation, management and collaboration in ports, promoting greater	Understand how the metaverse can be integrated into port systems to optimize their operations and	1. Assess the current state of technological readiness to embrace the metaverse. 2. Identify key applications of the metaverse in the port environment.

sustainability and global competitiveness?	improve environmental sustainability.	3. Explore socioeconomic and environmental benefits of the metaverse. 4. Develop a strategic framework for the adoption of the metaverse. 5. Design metrics to measure impact.
RQ4: How will the application of the ETS affect European ports, reconfiguring the economic, operational and environmental dynamics of the maritime sector?	Assess the economic impact of the ETS on European ports.	1. Identify economic implications for shipping companies. 2. Explore the phenomenon of carbon leakage. 3. Evaluate opportunities for technological innovation. 4. Analyze broader socioeconomic impacts.
RQ5: How can Bayesian networks help assess the sustainability of the marine renewable energy sector in Spanish ports, enabling better strategic decision-making?	To identify the key indicators that drive the sustainable development of the marine renewable energy sector in Spanish ports.	1. Select relevant indicators for the renewable energy sector. 2. Create a robust database. 3. Develop a Bayesian model to represent relationships between variables. 4. Assess sustainability challenges and opportunities in the sector. 5. Evaluate sustainability in the 3 dimensions.

1.3. Structure of the research

This doctoral thesis is organized into ten chapters, designed to comprehensively address the objectives set in the context of port sustainability, the Blue Economy and digitalization in Spanish ports.

Chapter 1 introduces the general context of the research, presenting the background related to sustainable development, the Blue Economy and emerging technologies. It also establishes the general and specific objectives of the research, as well as its justification and expected impact.

Chapter 2 develops the theoretical framework, analysing in detail the Strategic Framework of the Spanish port system, the principles of sustainability and their relationship with the Sustainable Development Goals (SDGs). In addition, the key concepts of the Blue Economy, its established and emerging sectors, and the role of emerging technologies in the port environment are discussed. This chapter culminates with the formulation of the research questions, the specific objectives and the hypotheses that guide this work.

Chapter 3 describes the methodology used, including the methodological tools used, such as Bayesian networks and affinity diagrams, as well as the research design structured in phases to analyse port sustainability.

Chapters 4 to 9 address the main results of the research:

- **Chapter 4** assesses the implementation of the Blue Economy sectors in Spanish ports, identifying disparities between the different port authorities and proposing strategies for improvement.
- **Chapter 5** explores the impact of digital transformation on Spanish ports, analysing digital governance, digital twins and the metaverse as tools to optimise operations and promote sustainability.
- **Chapter 6** details the use of end-to-end tools to analyse digital governance in ports, highlighting their contributions and benefits.
- **Chapter 7** discusses how the metaverse can reconfigure port operation and collaboration, based on an affinity diagram model.
- **Chapter 8** studies the economic impact of the implementation of the Emissions Trading System (ETS) in European ports, assessing different scenarios and their environmental and operational implications.
- **Chapter 9** applies Bayesian networks to assess the sustainability of the marine renewable energy sector in ports, identifying key indicators and developing predictive models.

Chapter 10 presents the general conclusions, limitations of the study and proposals for future research, highlighting the main scientific and practical contributions of this work.

1.4. Scientific contribution

The following scientific articles obtained as a result of the research project of this doctoral thesis are presented below. These articles have been re-printed between chapters 4 and 8 and are part of the main chapters of the dissertation.

- Title: *Evaluation of the Implementation of the Dimensions of the Blue Economy in Spanish Ports*
  Authors: Vaca Cabrero, J., Gómez Garach, C. P., Camarero Orive, A., & González-Cancelas, N.
  Journal: Journal of Marine Science and Engineering, 12(2), 222

Year: 2024. Journal Impact Factor (2024) (Q1) Social Impact Factor (2024) (Q2).
https://doi.org/10.3390/jmse12020222.

- Title: *Digital Transformation in Spanish Port System*
Authors: González-Cancelas, N., Camarero Orive, A., Vaca-Cabrero, J., & Soler Flores, F.
Journal: IntechOpen
Year: 2024. Journal Impact Factor Book (2024).
https://doi.org/10.5772/intechopen.1004329.
- Title: *Use of End-to-End Tool for the Analysis of the Digital Governance of Ports.*
Authors: González-Cancelas, N., Camarero Orive, A., Vilarchao, A. R., & Vaca-Cabrero, J.
Journal: Logistics, 8(2), 58
Year: 2024. Journal Impact Factor (2024) (Q2) Social Impact Factor (2024) (Q2).
https://doi.org/10.3390/logistics8020058
- Title: *Metaverse in ports through an affinity diagram.*
Authors: Vaca-Cabrero, J., González-Cancelas, N., Camarero-Orive, A., & Flores, F. S.
Journal: Journal of Infrastructure, Policy and Development, 8(5), 3303
Year: 2024. Journal Impact Factor (2024) (Q4) Social Impact Factor (2024) (Q2).
https://doi.org/10.24294/jipd.v8i5.3303
- Title: *Economic Impact of the Application of the ETS to European Ports: Analysis of Different Scenarios.*
Authors: Vaca-Cabrero, J., González-Cancelas, N., Camarero-Orive, A., Corral, M. M. E.-I., & Ricci, S.
Journal: Sustainability, 16(23), 10433
Year: 2024. Journal Impact Factor (2024) (Q2) Social Impact Factor (2024) (Q1).
https://doi.org/10.3390/su162310433
- Title: *Bayesian networks for assessing the sustainability of the Marine Renewable Energy sector in the Blue Economy of spanish ports.*
Authors: Vaca-Cabrero, J., González-Cancelas, N., & Camarero-Orive, A.

Journal: Sustainable Futures, 100497.
Year: 2025. Journal Impact Factor (2024) (Q2) Social Impact Factor (2024) (Q1).
https://doi.org/10.1016/j.sftr.2025.100497

2. THEORETICAL FRAMEWORK AND RESEARCH QUESTIONS

Chapter 2 establishes the theoretical framework that underpins this research, providing a conceptual basis for analysing port sustainability in the Spanish context. The 2022 Strategic Framework of the Spanish Port System is examined, which guides the transformation of ports towards sustainable models. Next, sustainability is addressed from a three-dimensional perspective (economic, environmental and social), highlighting its link with the Sustainable Development Goals (SDGs) and national and European policies. Subsequently, the Blue Economy, its principles and sectors are deepened, as well as the role of emerging technologies in the optimization of port operations and the promotion of sustainability. Finally, the research questions, objectives and hypotheses that will guide the analysis are presented, establishing a methodological framework in accordance with the challenges and opportunities of sustainable port development in Spain.

2.1. Strategic framework of the Spanish port system

The **2022 Strategic Framework of the Spanish Port System** is an ambitious and transformative roadmap that seeks to guide Spanish ports towards a model that integrates sustainability, resilience and technological innovation, with an execution horizon until 2030. This document is structured into 16 strategic lines and 56 general objectives that comprehensively address the economic, environmental and social dimensions [2]. This holistic approach is designed not only to modernise port infrastructures, but also to align their operation with the Sustainable Development Goals (SDGs), positioning ports as key nodes in the transition to a greener, more inclusive and digital economy. In addition, the framework reflects the principles of the Blue Economy, highlighting the role of ports as drivers of sustainability, innovation and regional economic growth.

From an economic point of view, the framework places a significant emphasis on the modernisation of port infrastructures, services and processes, with the aim of strengthening the global competitiveness of Spanish ports. This includes the adoption of disruptive technologies such as digital twins, the Internet of Things (IoT), and advanced automation [23]. These tools not only optimize logistics operations and reduce operating costs, but also increase energy efficiency and minimize environmental impacts. These innovations are essential to position Spanish ports as global benchmarks in maritime innovation and sustainability. In this context, the framework encourages business models based on the circular economy, promoting the efficient use of resources and reducing waste generation [24]. This approach is aligned with the objectives of the thesis, which seeks to explore how emerging technologies and the Blue Economy can be integrated to transform ports into engines of sustainable development.

Within this area, Strategic Line 7: Digital Port Administration stands out. Smart and Synchronous Ports, which establishes a clear framework for the comprehensive digitalisation of port processes. This approach includes the creation of cyber-physical systems and digital platforms that enable hyperconnection and process automation, positioning ports as intelligent and interconnected logistics nodes. Through concepts such as "Port as a Service" (PaaS), ports can offer digital solutions that improve the interaction between users and port systems, guaranteeing agility and security in operations. Likewise, the development of the synchrochrome port, which digitally connects ports with other logistics modes and nodes under a mobility-as-a-service (MaaS) framework, optimizes the efficiency and sustainability of global supply chains. These strategies are essential to modernise port management and are directly related to the objectives of the thesis, which analyses how digital tools can optimise port processes and promote sustainable practices [25].

From an environmental perspective, the strategic framework addresses as a priority the need to reduce the carbon footprint of the Spanish port system. This includes measures such as the electrification of infrastructure, the use of renewable energies and the implementation of advanced technologies to improve energy efficiency. These actions seek to transform ports into low-emission logistics nodes, contributing significantly to the fight against climate change [5]. Strategic Line 10: Environmentally Sustainable Ports deepens these priorities, promoting the integration of practices based on eco-efficiency, the sustainable management of resources such as water and energy, and the implementation of environmental monitoring systems that guarantee air, water and soil quality. These measures not only position ports as key players in the energy transition, but also ensure the protection of the marine and coastal ecosystems that surround them [7]. In the context of the thesis, these strategies are aligned with the exploration of how emerging technologies can be used to model sustainability scenarios and assess environmental impacts, contributing to a more balanced and responsible port development.

Complementing these actions, Strategic Line 11: Eco-Proactive Ports reinforces the commitment of port authorities to climate change mitigation and adaptation. This line promotes energy self-consumption projects, the use of alternative fuels and the reduction of emissions through incentives aimed at logistics operators. It also encourages the creation of environmental excellence programmes that reward actors who lead sustainable initiatives in the port sector [26]. In this sense, the thesis explores how tools such as digital twins and Bayesian networks can be used to plan investments in sustainability, prioritizing those that generate a greater impact in terms of decarbonization and climate resilience.

In the social sphere, the strategic framework pays special attention to the integration of ports with their local communities, promoting cultural and social projects that strengthen the link between port infrastructures and surrounding urban areas. This approach seeks to ensure that the benefits of port development are distributed equitably, generating positive impacts on society. Strategic Line 16: Scaling up and continuously improving Human Capital highlights the importance of preparing port workers to face the challenges posed by digitalisation and sustainability [2]. This objective includes the creation of continuous training programs that allow the development of skills in emerging technologies, such as IoT, digital twins and the metaverse. In addition, it promotes inclusive policies that promote gender diversity and the integration of people with disabilities in the port area. These initiatives not only improve working conditions, but also ensure that the benefits of technological transformation are sustainable in the long term [27], [28].

Innovation, for its part, is one of the fundamental pillars of the strategic framework, reflected in Strategic Line 8: Innovative Ports. This approach seeks to position ports as epicenters of technological development within the global economy. The creation of collaborative ecosystems to foster incremental and disruptive innovation is a key aspect of this strategy, aligning with the transition to the 4.0 economy. Initiatives such as the "Ports 4.0" programme are designed to incubate and accelerate technological projects that improve the sustainability and efficiency of port infrastructures. In addition, this line prioritises sectors such as marine renewable energies, biotechnology and the circular economy, highlighting the role of innovation in blue growth [16], [29]. This approach links directly to the objectives of the thesis, which analyzes how emerging technologies and Blue Economy principles can be integrated to maximize the positive impact of ports on economic and environmental development.

Finally, the integration of ports with their local communities and with the actors of the global logistics chain underscores the importance of collaborative governance in the implementation of the strategic framework. This approach encourages the active participation of port authorities, private companies, government bodies and local communities in strategic decision-making [30]. The thesis addresses this dimension by highlighting how collaboration between different actors can facilitate the adoption of innovative and sustainable practices, ensuring that the benefits of port transformation are distributed equitably and efficiently.

Overall, the 2022 Strategic Framework of the Spanish Port System provides a solid basis for transforming ports into sustainable, resilient and innovative models. The strategic lines related to digitalisation, environmental sustainability, innovation and the improvement of human capital are fundamental for the modernisation of the port system and are closely aligned with the objectives of the thesis. This comprehensive approach not only reinforces the role of ports as key players in the blue economy, but also positions them as global benchmarks in sustainability and technological innovation. By combining technology, sustainability and social inclusion, Spanish ports have the potential to lead the transition towards a more balanced and responsible economic model, contributing to the well-being of their local communities and the strengthening of international logistics chains.

2.2. Sustainability

2.2.1. Three-dimensional sustainability

Three-dimensional sustainability (economic, social and environmental) has established itself as an essential pillar in contemporary port management, recognising that ports play a crucial role beyond the transfer of goods and passengers. In an increasingly globalised world, ports have become strategic nodes of international logistics networks, with 80% of imports and 60% of exports in Spain transiting through them. This economic centrality places ports in a privileged position to lead the transition towards development models that balance the economic, social and environmental dimensions.

From an economic perspective, port sustainability involves optimizing logistics operations to reduce costs, improve efficiency, and increase the overall competitiveness of ports. This not only translates into investments in innovative technologies such as digital twins, the Internet of Things (IoT) and automation, but also into the development of business models based on the circular economy. For example, measures such as the electrification of port machinery and the implementation of renewable energy have proven effective in reducing operating costs and carbon emissions. According to studies by [1], [31], these investments are critical not only to ensure economic sustainability, but also to meet the United Nations Sustainable Development Goals (SDGs), which call for a balance between economic growth and environmental protection.

In the environmental field, port sustainability encompasses the adoption of practices and technologies that minimize the negative impact of port activities on marine and coastal ecosystems. Initiatives such as the use of renewable energies, efficient waste management and the reduction of greenhouse gas emissions have become particularly relevant in recent years. In particular, the European Green Deal and the Fit for 55 programme have established a regulatory framework that requires European ports to move towards carbon neutrality by 2050 [32], [33]. These efforts are supported by the development of advanced environmental monitoring systems that allow for real-time assessment of the impact of port activities on the environment. [34] They highlight that these systems not only help mitigate the effects of climate change, but also improve the resilience of ports in the face of extreme weather events, such as sea level rise and severe storms.

The social dimension of port sustainability is also fundamental, as it addresses aspects such as the generation of inclusive employment, the improvement of working conditions and the integration of local communities in port activities. Ports are not only economic engines, but also spaces for social and cultural interaction. This underscores the importance of ensuring that local communities are involved in strategic decision-making related to port development. Studies such as those in [35] have shown that community participation in port planning can significantly increase the acceptance of development projects, as well as improve social cohesion.

A concrete example of how ports can integrate these three dimensions of sustainability is the case of the Port of Vigo, which has implemented the "Blue Growth" strategy to promote an inclusive, innovative and ecological port model with a view to 2027 [8]. This approach includes the adoption of advanced technologies, the promotion of renewable energy projects, and collaboration with local communities to ensure balanced and sustainable development. Similarly, the Port of Barcelona is leading initiatives such as "Blue-Up", which seeks to promote innovation and sustainability through public-private collaboration.

However, achieving three-dimensional sustainability in ports is not without its challenges. Among the main barriers are the lack of technological interoperability, resistance to organizational change and budget constraints. In addition, there is an urgent need to develop more accurate and consistent sustainability indicators to effectively assess progress. Ref. [36] highlight that current indicators often lack standardization, making it difficult to compare between different ports and regions.

In this sense, methodological tools such as Bayesian networks and affinity diagrams can play a crucial role in overcoming these limitations. These tools allow complex relationships between economic, social and environmental variables to be analyzed, providing a solid basis for strategic decision-making. In addition, the Delphi method, widely used in sustainability research, facilitates the integration of expert perspectives to identify priority areas for intervention.

In conclusion, three-dimensional sustainability in ports is an ambitious but achievable goal, as long as a holistic approach is adopted that integrates the economic, social and environmental dimensions. The reviewed studies and featured case studies demonstrate that ports can become leaders in the transition to a greener and more digital economy. To achieve this, it is essential to foster collaboration between all actors involved, promote technological innovation and ensure that the benefits of port development are distributed equitably between local communities and the environment.

2.2.2. Relationship with the SDGs and national and European policies

The integration of the Sustainable Development Goals (SDGs) into port management has provided a clear framework to guide policies and practices towards sustainability [1]. Several SDGs are directly relevant to ports, highlighting the following:

- **SDG 9: Industry, innovation and infrastructure.** Ports play a key role as logistics nodes that drive connectivity and sustainable industrialization. In this regard, the Strategic Framework promotes the modernisation of port infrastructures through digital technologies such as blockchain, artificial intelligence and digital twins, improving efficiency and reducing operational costs.
- **SDG 13: Climate action.** The fight against climate change is a priority on the port agenda. EU-led decarbonisation policies, such as the Emissions Trading System (ETS), seek to transform ports into low-emission spaces by electrifying docks and promoting alternative fuels such as hydrogen.
- **SDG 14: Life below water.** Ports also have a direct impact on marine ecosystems. Therefore, sustainable management includes measures to prevent water pollution, promote marine biodiversity and develop economic activities linked to the Blue Economy, such as aquaculture and marine renewable energies.
- **SDG 17: Partnerships to achieve the Goals.** Ports foster partnerships between the public and private sectors, local communities and international organizations to achieve common goals. An example of this are collaborations to implement sustainable infrastructures and develop research projects in innovation and sustainability.

2.3. Blue Economy: definition, principles and sectors.

2.3.1. A new model of economic development

The Blue Economy emerges as an economic model that differs from the Green Economy due to its regenerative and circular approach. According to [9]), while the Green Economy has promoted greater investments to develop sustainable goods and services, the additional cost has fallen mainly on consumers, generating a model that, although environmentally conscious, has not always demonstrated economic viability. In contrast, the Blue Economy seeks to guarantee the proper functioning of ecosystems, respecting their evolutionary processes and adopting regeneration as a fundamental principle.

This approach states that any waste, whether material or energetic, can become a resource for new production processes. In this way, the problem does not lie in the generation of waste, but in its inefficient management. The Blue Economy imitates nature, where ecosystems operate without waste, achieving a balance in which the waste of one living being is raw material for another. In Pauli's words, by shifting from a linear to a cyclical perception, we not only reshape our practices, but also ensure that everyone's basic needs are met, promoting the well-being of both the planet and its inhabitants.

This model has gained global acceptance in the last decade, being adopted by organizations such as the United Nations, the European Union, and the World Bank [13]. Its integration into development agendas seeks to ensure that human activities linked to the oceans and marine resources are carried out in a sustainable manner, respecting environmental limits while promoting economic growth and social equity.

2.3.2. The Blue Economy and its international development

The concept of the Blue Economy was formally recognized at the United Nations Conference on Sustainable Development in 2012, held in Rio de Janeiro. At that meeting, the oceans and seas were placed at the center of the agenda, highlighting their essential role in global sustainability. The United Nations stressed that green development must evolve towards a Blue Economy, especially in coastal and maritime regions that depend heavily on marine ecosystems [1], [11].

Since then, the model has evolved towards a more transversal approach, integrating traditional and emerging economic sectors. The Blue Economy is not only limited to sea-related activities such as fishing and shipping, but also encompasses innovative areas such as marine renewable energy, biotechnology and the circular economy. These activities are seen as opportunities to stimulate economic growth, generate employment and address environmental challenges such as marine pollution and climate change.

At the European level, the Blue Economy has become a strategic pillar. The European Commission defines Blue Growth as a long-term initiative to support the sustainable development of the marine and maritime sectors. According to this vision, the oceans and seas have the potential to be economic engines, especially through innovation and sustainable growth. In this context, financing policies and programmes have been implemented, such as the Recovery and Resilience Fund, which allocates 37% of its budget to the green transition, including projects related to the Blue Economy.

2.3.3. Blue Economy Sectors

The Blue Economy is made up of a wide variety of sectors, which the European Commission divides into two main categories: established sectors and emerging sectors. These sectors not only generate a significant economic impact, but also have the potential to lead the transition to a more sustainable model.

Although in the 2024 report [13] the European Union presents a revised classification that includes 9 sectors, the classification used in the 2021 report will be adopted in this thesis, as it offers a more detailed and relevant structure for the objectives of the study [37]. This approach distinguishes between established sectors, which include 7 traditional activities with a track record of making a significant contribution to economic growth, and **emerging sectors**, which comprise 6 innovative areas with high potential to drive the transition to sustainability and digitalisation. This classification allows for a more granular analysis of the economic, social and environmental impacts of the Blue Economy, aligning with the fundamental principles of this research.

2.3.3.1. Established Industries

The established sectors of the European Union's Blue Economy represent a solid foundation for the continent's economic growth and sustainability. In 2018, these sectors generated a gross value added (GVA) of €176.1 billion, an increase of 15% compared to 2009. In addition, gross operating surplus reached €68.1 billion, up 14% on 2009, while total turnover amounted to €649.7 billion, up 13% over the same period. In terms of employment, approximately 4.5 million people were directly employed in these sectors in 2018, 1% more than in 2009, representing a significant recovery from the 2008 financial crisis and a 12% increase from the previous year (2017). This growth was mainly driven by coastal tourism, which saw a 20% increase in jobs since 2017, and marine renewables, which increased the number of workers by 22 times since 2009.

Among the established sectors, living marine resources stand out for their economic relevance. This sector, which includes fisheries and aquaculture, accounted for 10.8% of the Blue Economy's GVA, equivalent to almost €20 billion. Spain leads this sector with 21% of employment and 19% of the value generated, especially in primary activities such as fish capture and processing of marine resources. However, distribution in this area is dominated by Germany, highlighting a competitive dynamic within the European market.

The inert marine resources sector, focused on the extraction of oil, gas and materials such as sand and gravel, also plays a crucial role in the EU's maritime economy. Countries such as Denmark, the Netherlands and Italy lead in wealth generation and employment in this area, closely linked to port activities that support the construction and maintenance of related infrastructures.

On the other hand, offshore renewables, led by offshore wind, have experienced exponential growth since 2009. Europe accounts for 90% of the world's installed capacity, with Germany, Belgium, Denmark and the Netherlands being the most developed countries in this sector. These activities are intimately related to other established sectors, such as shipbuilding and repair and port activities, underlining the interconnectedness between the different areas of the Blue Economy.

Port activities are another strategic sector, handling 82% of imports and 74% of EU tonnage exports. In 2016, maritime passenger transport reached 420 million, consolidating the importance of ports as key logistics nodes. Countries such as Germany, the Netherlands, Spain and France lead in terms of GDP generation and employment in this sector. The Atlantic Maritime Strategy, adopted by the EU in 2011 and updated in 2020, underlines the need to finance smart infrastructure that promotes sustainable growth, decarbonisation and adaptation to climate change.

The shipbuilding and repair industry also plays a prominent role, with Europe leading globally. Countries such as Germany, Italy and France dominate this sector, which includes the construction, repair and maintenance of ships and floating structures, as well as related equipment. Despite advances in environmental sustainability, this sector faces significant challenges, such as the need to reduce emissions and compete with emerging powers such as China and South Korea.

Maritime transport, which includes the transport of passengers, goods and related services, is fundamental to the global economy and decarbonisation. It accounts for 17% of the Blue Economy's GDP, 9% of employment and 21% of profits. Germany leads this sector with 35% of employment and 37% of GDP, followed by Italy, reflecting its importance in international connectivity and global trade.

Finally, coastal tourism is the largest sector in terms of GDP and employment within the Blue Economy. This sector generates 10% of the EU's GDP and employs 23 million people, with 37% of workers under the age of 35. Spain leads this area with 26% of employment and 30% of GDP, consolidating itself as a key tourist destination. Countries such as Portugal, Italy, Malta and Greece also stand out, especially in coastal areas. However, coastal tourism faces significant challenges related to climate change, such as rising sea levels, erosion and storms. Despite these challenges, cruise tourism has continued to grow, with a global impact of €129 billion in 2019, placing Europe as the leading cruise ship builder and the second most popular destination globally.

In summary, established Blue Economy sectors not only generate significant economic impact, but also play a crucial role in the transition to more sustainable models. Their interconnectedness with technological innovation, environmental sustainability and climate resilience positions them as key pillars for the EU's economic growth, highlighting the need for integrated strategies that promote both competitiveness and long-term sustainability.

2.3.3.2. Emerging sectors

The emerging sectors of the Blue Economy represent one of the most dynamic and innovative areas within this economic model, as they are oriented towards the development of advanced technologies and sustainable solutions that contribute significantly to the transition to a greener and more digital economy. However, as the European Commission points out, the accurate measurement of the contribution of these sectors still faces limitations due to the lack of standardized data and the complexity of their activities. Despite these difficulties, their potential to transform the maritime economy is undeniable, placing them as key players in the future of the Blue Economy.

The ocean energy sector is one of the most promising, focusing on the development of innovative renewable sources such as offshore floating wind, tidal power, floating PV plants, and offshore hydrogen generation. These technologies not only diversify renewable energy sources, but also make it possible to take advantage of deep-sea areas, which until now had not been exploited. Its implementation is aligned with the European Union's decarbonisation objectives, which seek to reduce greenhouse gas emissions and ensure a sustainable and diversified energy supply.

The blue economy and biotechnology is another emerging sector that promises a significant impact on sustainable development. This sector takes advantage of marine biomass, such as algae, bacteria and fungi, to develop commercial applications in food, cosmetics and fertilizers, as well as innovations such as biomaterials and biofuels. Since 2014, the European Union has co-financed projects aimed at promoting this industry, with countries such as Spain, France, Ireland and Norway standing out for leading the number of companies dedicated to the cultivation and transformation of macroalgae.

The desalination sector also ranks high among emerging ones, especially in Mediterranean regions that face growing freshwater supply problems. According to the European Union report, Spain leads this area with 65% of the continent's desalination capacity. Technologies such as reverse osmosis, electrodialysis and multi-effect evaporative distillation are key to ensuring water supply in contexts of scarcity, thus supporting both economic development and the resilience of coastal communities.

On the other hand, maritime mining, although traditional in its essence, is included among the emerging sectors due to its potential in supplying essential materials for high technology, such as batteries and electronic devices. The extraction of minerals from the seabed opens up new opportunities to meet the growing demand for technological resources, although it poses significant challenges related to environmental sustainability and the management of impacts on marine ecosystems.

The maritime defence, security and surveillance sector has also gained importance, with large investments by the Member States of the European Union. The European Maritime Security Strategy seeks to ensure the protection of citizens and maritime interests in the region, strengthening the capacity to respond to threats and promoting a safe maritime environment.

Research and education is a cross-cutting axis in the development of the emerging Blue Economy. This sector not only promotes knowledge about marine and coastal ecosystems, but also promotes a green and digital transition through programmes such as the European Horizon, which has a budget of more than 95,000 million euros for the period 2021-2027. These initiatives support the climate neutrality of maritime industries and the development of smart territories connected to land and sea, promoting sustainability and innovation in the port area.

The infrastructure sector is another crucial component of the emerging sectors, with a focus on improving the submarine cable network to strengthen telecommunications. In addition, it includes innovative initiatives such as the use of sustainable materials to reduce emissions during port construction and facilitate the regeneration of marine ecosystems in obsolete structures, such as through the use of econcrete and treatment with calcium carbonate.

Taken together, the emerging sectors of the Blue Economy reflect the direction in which the maritime economy is moving: towards greater sustainability, innovation and resilience. While they still face challenges in terms of assessment and regulation, their potential contribution to environmental sustainability and economic development is crucial to achieving the European Union's strategic objectives in the context of an inclusive and ecologically responsible Blue Economy.

2.3.4. The Blue Economy in Spain

Spain plays a leading role in the European Blue Economy. With more than €33 billion in GVA and more than 900,000 jobs generated, the country leads several key sectors, including coastal tourism, living marine resources and port activities. In addition, Spanish ports, such as those of Algeciras, Barcelona and Vigo, are benchmarks in the implementation of sustainable practices and in the promotion of economic activities related to the Blue Economy.

In recent years, Spain has developed innovative initiatives in this area. For example, the port of Vigo has adopted strategies to reduce carbon emissions, promote marine biotechnology and encourage the use of renewable energies. These actions reflect Spain's commitment to the transition to a blue economic model, aligned with European sustainability goals [37].

2.3.5. Policies and financing for the Blue Economy

The success of the Blue Economy depends largely on policies and adequate funding. In Europe, the European Commission has launched several programmes to support this transition. The Recovery and Resilience Fund, for example, allocates a significant part of its budget to projects related to the Blue Economy, such as sustainable port infrastructure and offshore renewable energy plants [13].

In addition, the BlueInvest Fund finances innovations in areas such as marine biotechnology and renewable energy. These initiatives seek to attract investment and promote collaboration between the public and private sectors, ensuring that the benefits of the Blue Economy are equitably distributed [16].

The Blue Economy is presented as a transformative model that combines sustainability and economic development. Inspired by the natural regeneration of ecosystems, this approach offers solutions to the environmental and economic challenges of the 21st century. Spain, as a leader in this field, has the opportunity to consolidate its position through policies that promote innovation, sustainability and international cooperation.

2.4. Emerging technologies in the port sector

2.4.1. Digital transformation in the port sector

The digital transformation in the port sector represents a radical change in the way operations are managed and the flow of goods, services and information is organized. Ports have evolved from simple transit points for goods to complex logistics hubs, where technology plays an essential role in competitiveness, sustainability and resilience. The digitalization process seeks to optimize operations, improve the user experience and, at the same time, respond to the challenges of climate change and globalization.

At the heart of this transformation are disruptive technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), and Blockchain. These tools enable a constant flow of data that, when managed effectively, provide real-time information about the logistics chain, from the arrival of a vessel to the final delivery of cargo [38]. Data, combined with machine learning algorithms, facilitates evidence-based decision-making, increasing accuracy and reducing margins of error in critical operational processes [24].

In addition, digital transformation not only seeks to improve operational efficiency, but also prioritizes sustainability. The adoption of technologies for the electrification of docks, the optimization of logistics routes and the implementation of energy management systems are concrete examples of how ports are reducing their carbon footprint. This transition also responds to growing customer demands and international regulations, such as the European Green Deal, which requires ports to adopt more sustainable practices [32].

An illustrative example of this transformation is the port of Valencia, which has incorporated advanced data analysis platforms to manage its operations, allowing the optimization of resources and the reduction of waiting times. Other ports, such as Barcelona, are integrating digital twin technologies and simulations to improve strategic planning and emergency management.

2.4.2. Digital governance and smart ports

Digital governance is an essential pillar in the transformation of ports into smart logistics ecosystems. It refers to the strategic use of data and technologies to plan, coordinate and monitor port operations, ensuring their transparency, efficiency and sustainability. This trend not only responds to the need to modernize infrastructure, but also to the demands of a more dynamic and connected global logistics.

In practice, digital governance involves the creation of integrated management platforms that centralize data from multiple sources, such as IoT sensors, maritime traffic systems, customs databases, and e-commerce platforms. These tools allow port authorities to make decisions based on real-time information, optimizing logistics flows and minimizing disruptions. In addition, they encourage collaboration between the different actors in the logistics chain, such as operators, customs agents and land transporters [39].

A key component of digital governance is the concept of the "smart port," which combines advanced technologies with physical and digital infrastructures to improve operational efficiency. Smart ports not only process large volumes of data, but also use predictive algorithms to anticipate problems and propose solutions. For example, they can anticipate congestion at the docks and reschedule operations to avoid delays, or detect security vulnerabilities and activate preventive measures [40].

Digital governance also has a direct impact on sustainability. By managing resources more efficiently, ports can reduce their energy consumption and minimize the environmental impact of their operations. In addition, it facilitates the implementation of circular economy policies, such as the reuse of materials and the electrification of ships during berthing, thus reducing polluting gas emissions [41].

2.4.3. Digital twins: revolution in planning and operation

Digital twins represent one of the most innovative tools in port digitalisation. These virtual models, which replicate physical infrastructures and operating systems, allow processes to be simulated and analyzed in real time, providing a comprehensive view of port operations. Its application ranges from logistics optimization to strategic planning and emergency management [42].

One of the main advantages of digital twins is their ability to foresee problems before they occur. By integrating real-time data, these models allow port managers to evaluate different operational scenarios and make informed decisions. For example, in the event of congestion at a dock, the digital twin can propose alternative solutions to redistribute the load and minimise delays [19].

In addition, digital twins are essential to improve sustainability in ports. They can optimize logistics routes, reducing fuel consumption and carbon emissions. They also facilitate the structural monitoring of infrastructures, identifying possible failures and planning their maintenance efficiently. In terms of safety, digital twins make it possible to simulate emergency situations, such as fires or spills, to assess the system's response and improve existing protocols [43].

Digital twins are also transforming port infrastructure planning. By analyzing historical data and projecting future scenarios, these tools help design more resilient infrastructures adapted to the needs of global trade. For example, they can assess the impact of an increase in maritime traffic or the effects of climate change on port operations [20].

2.4.4. The virtual universe as an ecosystem of port innovation

The metaverse, a shared and persistent virtual space, is emerging as a revolutionary tool in port management. This concept goes beyond virtual representation, offering an interactive environment where users can participate in simulations, training, and collaborations in real time [18].

One of the most promising applications of the metaverse in ports is the creation of metaports, virtual replicas of physical port infrastructures that allow managers to operate and plan more efficiently. In a metaport, operators can interact as avatars, simulating logistics operations and assessing the impact of different decisions without disrupting actual operations. This is particularly useful for training operators in new technologies or preparing for emergency responses.

In addition, the metaverse facilitates collaboration between the different actors in the logistics chain. For example, customs authorities, port operators, and carriers can work together in a virtual environment to coordinate operations and solve problems in real time. Technologies such as Blockchain and Augmented Reality (AR) extend the capabilities of the metaverse, integrating data into interactive layers that improve the accuracy and efficiency of operations [27].

The metaverse also has a significant impact on sustainability. By enabling operations simulation, it reduces the need for physical tests that consume resources and generate emissions. In addition, it encourages innovation, offering a space to experiment with new technologies and concepts before implementing them in the real world [44].

2.4.5. Other key tools of port digitalisation

In addition to digital twins and the metaverse, there are other technologies that are transforming ports into smart ecosystems:

Blockchain: This technology guarantees transparency and security in logistics transactions. It allows the movement of goods to be tracked throughout the supply chain, reducing fraud and improving administrative efficiency [21].

Internet of Things (IoT): IoT sensors collect real-time data on the state of infrastructure, maritime traffic, and weather conditions, facilitating data-driven decision-making [22].

Artificial Intelligence (AI): AI algorithms analyze large volumes of data to identify patterns and propose solutions. For example, they can predict peaks in demand or recommend adjustments in logistics operations [24].

Autonomous vehicles: Automation of cranes, trucks, and vessels reduces loading and unloading times, improving operational efficiency and safety [45].

In short, digitalisation in ports is not only a trend, but a necessity to guarantee their competitiveness and sustainability in a globalised world. Tools such as digital twins, the metaverse, blockchain, and IoT are transforming the way ports operate, plan, and collaborate. However, to make the most of these technologies, it is critical to overcome challenges such as interoperability, cybersecurity, and resistance to change. With strong digital governance and a commitment to innovation, ports are well-positioned to lead the transition to a more efficient, sustainable and interconnected future.

2.5. Port community's influence on the Blue Economy and emerging technologies

The development of the Blue Economy and the adoption of emerging technologies in ports do not depend exclusively on Port Authorities. The port community, made up of public and private agents, plays a fundamental role in the definition, implementation and consolidation of these initiatives. This ecosystem includes logistics operators, shipping companies, terminal concessionaires, marine renewable energy companies, shipyards, research institutes and business associations, among others. The interaction between these actors is key to achieving a sustainable, resilient and competitive port development model.

2.5.1. Collaborative governance in the Blue Economy

The transition to a model based on the Blue Economy requires collaborative governance where the Port Authority acts as a facilitator, but private agents drive innovation and investment. A clear example is the development of marine renewable energies, where private companies lead the research and implementation of wind and wave energy infrastructures, while the Port Authority provides the regulatory framework and spaces for their development.

Blue Economy clusters have proven to be key tools for fostering public-private collaboration, aligning the interests of different actors to maximize the sustainability and profitability of projects. In Spain, initiatives such as "Blue Growth Vigo" have managed to integrate digitalisation, innovation and sustainability into port management, generating a model that can be replicated in other ports. In addition, the strategic plans of some ports, such as Barcelona and Valencia, include specific programmes to encourage the transition to a more sustainable port economy.

For collaborative governance to be effective, it is essential to establish fluid communication mechanisms between the different actors in the port community. The creation of sectoral roundtables, participation in European consortia and the development of dialogue platforms are key strategies to ensure the inclusion of all stakeholders.

2.5.2. Digitalisation and the role of private actors

Emerging technologies, such as artificial intelligence, blockchain, and digital twins, are transforming port operations. Private companies have led its implementation with significant investments in solutions that optimize cargo management, merchandise traceability, customs process automation, etc. For example, the Port Community System (PCS), largely promoted by both public entities and the different private agents involved in the different links of the logistics chain, have improved interconnectivity, synchromodality and transparency in port transactions.

The development of virtual ecosystems, which integrate immersive technologies, depends to a large extent on collaboration between technology companies and players in the logistics sector. These digital ecosystems allow for more efficient planning and operation, improving real-time decision-making and reducing operational costs. Terminal automation and the use of autonomous vehicles in port management are also significant developments in this area.

In addition, the implementation of these technologies allows greater adaptability to regulatory changes, as it facilitates compliance with environmental and safety regulations. Ports that have opted for digitalisation may be better positioned to meet the challenges of international trade and the transition to a decarbonised economy.

2.5.3. Impact on sustainability and competitiveness

The impact of the port community on the Blue Economy and digitalisation is also reflected in sustainability and competitiveness. Companies are increasingly involved in decarbonization projects through the use of alternative fuels, the electrification of docks and the implementation of circular economy strategies in waste management.

In terms of competitiveness, ports that achieve greater synergy between their public and private actors will be able to position themselves as global benchmarks. The case of the Port of Rotterdam, with its digital innovation hub and collaboration platform for the energy transition, exemplifies how the integration of these actors drives leadership in sustainability and logistics efficiency.

Environmental certification programs, such as the PERS (Port Environmental Review System), have also gained relevance in ports seeking to improve their ecological performance. Investment in clean technologies and the optimisation of energy consumption are determining factors in reducing the carbon footprint of the port sector.

2.5.4. Challenges and opportunities

Despite the crucial role played by the port community in the transition to the Blue Economy and digitalisation, there are still significant challenges that need to be addressed. The interoperability and standardization of digital systems continues to be an obstacle, since the diversity of technologies hinders integration throughout the logistics chain, it is here that the role of the public agent as regulator and facilitator plays a key role. In addition, digitalization and the adoption of new technologies require significant investments with long-term returns, which represents a financial challenge for many companies in the sector. On the other hand, cybersecurity becomes a critical aspect, given that automation and intensive use of data increase exposure to digital threats.

Overcoming these challenges will make it possible to consolidate a more sustainable, resilient and competitive port ecosystem, where collaboration between the Port Authority and private agents is the driving force behind the transformation of the sector. With a strategic and coordinated approach, ports can become global benchmarks for innovation, efficiency and sustainability.

2.6. Research questions, objectives, and hypotheses

The analysis of port sustainability in Spain, framed within the Blue Economy and emerging technologies, requires a methodological approach that allows the evaluation of both the structural factors and the operational dynamics that affect the sustainable development of ports. Based on the Strategic Framework of the Spanish Port System and the conceptualization of three-dimensional sustainability, this research poses a series of research questions aimed at understanding the degree of implementation of the Blue Economy, the impact of emerging technologies on port processes and the influence of environmental regulations on the competitiveness of the sector. These issues are structured around five fundamental axes that address the integration of sustainability, digitalization, technological innovation, digital governance and decision-making based on advanced analytical models. Based on these questions, the general and specific objectives of the research are established, as well as the hypotheses that will guide the empirical analysis and contribute to generating knowledge applicable to the modernization and sustainability of the Spanish port system.

- **RQ1. What is the degree of implementation of the Blue Economy sectors in Spanish ports and how does it vary between the different port authorities?**

The sustainable development of ports and their alignment with the principles of the Blue Economy have become fundamental pillars to address contemporary challenges such as climate change, the energy transition or the efficient management of marine resources. In this context, the Blue Economy, as a regenerative and circular model, offers an ideal framework to integrate coastal and maritime economic activities with sustainable practices that promote biodiversity and the resilience of marine ecosystems. However, the implementation of this model in Spanish ports still presents significant disparities that need to be evaluated and understood.

In this scenario, the main research question that guides the analysis arises: **What is the degree of implementation of the Blue Economy sectors in Spanish ports and how does it vary between the different port authorities?** This question allows the analysis to be structured towards the identification of the factors that influence the uneven development of the Blue Economy in the 28 Port Authorities in Spain, as well as to evaluate their impact on the economic, social and environmental dimensions. In answering this question, it seeks not only to understand the current state of the established and emerging sectors, but also to propose strategies to overcome the gaps and maximize the potential of this economy in the port context.

The main objective of this analysis is to develop a model that assesses the degree of implementation of the Blue Economy sectors in Spanish ports. This model will not only serve to measure the current state of development, but also as a tool to identify strengths, weaknesses and opportunities that can guide strategic decision-making. Through this approach, it is intended to promote a more balanced and sustainable development between the different port authorities, contributing to the strengthening of their capacities and the fulfilment of the Sustainable Development Goals (SDGs).

In detail, the analysis pursues several specific objectives. The first of these is to design a robust methodological model that allows the development of the established and emerging sectors of the Blue Economy in ports to be systematically evaluated. These sectors, which include activities such as coastal tourism, fishing, marine renewable energies and biotechnology, have high potential to boost economic and environmental sustainability in port environments. However, their development is not homogeneous, and a tool is required to evaluate these differences and prioritize the necessary interventions.

A second key objective is to identify the disparities in the development of the Blue Economy sectors between the different Spanish ports. These differences can be influenced by factors such as geographical location, port size, operational capacity, and strategies adopted by port authorities. Identifying these disparities is crucial to design specific policies that address the particular needs of each port and maximize its contribution to sustainable development.

Third, the analysis seeks to assess the impact of established and emerging Blue Economy sectors on the economic, social and environmental development of ports. While established sectors, such as shipping and traditional port activities, have historically been the economic drivers of ports, emerging sectors, such as marine renewables and biotechnology, represent new opportunities to diversify the economy and reduce reliance on carbon-intensive activities. This objective involves not only measuring the current impact of these sectors, but also projecting their future contribution under different development scenarios.

Finally, the fourth specific objective is to propose strategies based on the results of the model to improve the implementation of the Blue Economy in ports with less development. These strategies should be aligned with the principles of sustainability and resilience, fostering collaboration between different port authorities, as well as with the private sector and local communities. In addition, it is expected that these proposals will serve as a reference for the replication of the model in other international contexts, positioning Spain as a leader in the transition to the Blue Economy.

To address these objectives, several hypotheses are put forward that guide the analysis and allow the expectations of the results to be structured. The first hypothesis (H1) states that the established sectors of the Blue Economy are more developed than the emerging sectors in Spanish ports due to their lower economic risk and greater technological maturity. This hypothesis reflects a common reality in many economic sectors, where consolidated activities tend to receive greater support and financing compared to those that, although innovative, imply a greater degree of uncertainty.

The second hypothesis (H2) suggests that there are significant disparities in the degree of implementation of the Blue Economy among Spanish ports, influenced by factors such as geographical location, port size and management strategy. For example, ports with greater access to natural resources, such as marine renewable energy, or those located in regions with a more established fishing tradition, may show greater development compared to others that face geographical or economic constraints.

Finally, the third hypothesis (H3) states that ports with a greater development of emerging sectors experience a greater positive impact in terms of sustainability and economic diversification compared to those focused on traditional sectors. This hypothesis highlights the transformative potential of the emerging sectors of the

Blue Economy, which not only contribute to environmental sustainability, but also to job creation and the strengthening of local economies.

In summary, the analysis of the Blue Economy in Spanish ports not only seeks to answer fundamental questions about its current and future state, but also to provide tools and strategies that guide its development towards a more sustainable and equitable model. The objectives and hypotheses put forward offer a comprehensive framework to understand and address the challenges and opportunities of this transition, positioning ports as key actors in the economy of the 21st century.

- **RQ2. How can digital technologies transform the operations and sustainability of Spanish ports in a global logistics environment?**

The digital transformation of the Spanish port system marks a critical evolution in the way ports manage their operations, promote sustainability and compete in a global logistics environment. This change not only implies the incorporation of advanced technological tools, but also a comprehensive reformulation of the processes, structures and strategies that define the port sector. In this context, a research question arises that articulates the analysis and proposals for improvement: **How can digital technologies transform the operations and sustainability of Spanish ports in a global logistics environment?**

Answering this question requires a thorough understanding of the current and potential dynamics of digitalization in ports, as well as an analysis of the benefits, challenges, and limitations associated with the adoption of emerging technologies. This central issue is not limited to identifying the technologies that are already being implemented, but also explores how these can be scaled, integrated and optimised to ensure that Spanish ports are consolidated as global benchmarks in efficiency, sustainability and competitiveness.

To address this question, the study relies on a set of specific goals that break down the key areas of digital transformation. These goals not only assess the progress made to date, but also identify critical gaps and propose strategies to overcome them. Thus, digital transformation is not conceived as a goal in itself, but as a means to achieve broader goals related to environmental sustainability, operational efficiency, and economic growth.

The general objective of this analysis is to identify and analyse the key factors driving digital transformation in the Spanish port system, assessing their impact on fundamental areas such as operational efficiency, environmental sustainability and international competitiveness. This central objective reflects the need to adopt a holistic approach that connects technology with the economic, social and environmental challenges facing ports in the 21st century.

As for the specific objectives, the first focuses on assessing the current state of digitalisation in Spanish ports. This involves identifying emerging technologies that are being implemented, such as digital twins, the metaverse, and the Internet of Things (IoT), and analyzing their impact on key areas such as operational security, resource management, and process optimization. This analysis is essential to establish a baseline to measure progress and design effective interventions.

The second objective seeks to propose a strategic framework for digital governance, understood as the ability to integrate advanced technological tools in a collaborative environment. In this sense, the framework should facilitate the adoption of technologies that improve the efficiency and sustainability of port operations, while promoting cooperation between the 28 port authorities in Spain. Digital governance is not only based on the implementation of technologies, but also on the creation of collaborative ecosystems where data and processes are shared securely and efficiently.

A third objective is to analyse the challenges and opportunities presented by digitalisation. This analysis includes barriers such as technological interoperability, cybersecurity, and resistance to organizational change. For example, a lack of common standards can make it difficult to integrate systems, while concerns about data security can limit the adoption of advanced technologies. Identifying and mitigating these obstacles is essential to ensure a successful digital transition.

The fourth objective addresses the need to promote the integration of sustainability into digitalisation processes. In this context, it will assess how the adoption of digital technologies can contribute to goals such as reducing carbon emissions, efficient use of resources and protecting marine ecosystems. This approach underscores the importance of aligning digital transformation with global sustainability goals, such as the Sustainable Development Goals (SDGs).

Finally, it is proposed to develop indicators to measure the impact of digital transformation. These indicators should provide port authorities with practical tools to assess progress, identify areas for improvement and adjust their strategies on an ongoing basis. Accurate impact measurement is crucial to ensure that technology investments generate tangible and sustainable benefits.

The analysis is also guided by a series of hypotheses that structure expectations about the impact of digitalisation on Spanish ports. The first hypothesis (H1) posits that the adoption of advanced technologies, such as digital twins, IoT, and the metaverse, significantly improves the operational efficiency and competitiveness of ports. These technologies make it possible to simulate operations, optimize logistics routes and predict problems before they occur, which translates into a reduction in costs and an improvement in response capacity.

The second hypothesis (H2) suggests that ports that integrate digital governance and sustainability strategies obtain greater economic, social and environmental benefits. For example, digitalization can facilitate the electrification of docks, reducing carbon emissions, or allow the implementation of circular economy practices that optimize the use of resources. The alignment between technology and sustainability not only improves the reputation of ports, but also allows them to comply with environmental regulations and attract new business opportunities.

Finally, the third hypothesis (H3) identifies the lack of technological interoperability and organizational resilience as the main challenges for effective digitalization. These barriers limit the ability of ports to integrate systems and processes, which in turn reduces efficiency and hinders the adoption of new technologies. Overcoming these challenges requires not only investment in technological infrastructure, but also a cultural shift that fosters innovation and adaptability.

In summary, the digital transformation of the Spanish port system represents a unique opportunity to redefine its role in the global economy. By addressing fundamental questions, setting clear targets, and formulating robust hypotheses, this analysis provides a comprehensive framework to guide the digitalization process, ensuring that ports not only respond to current challenges, but also lead the transition to a more efficient, sustainable, and interconnected future.

- **RQ3. How can virtual universes transform the operation, management and collaboration in ports, promoting greater sustainability and global competitiveness?**

The metaverse has emerged as a disruptive technological innovation with the ability to transform a wide variety of sectors, including the port sector. Its multifaceted nature positions it not only as a technological tool, but as a comprehensive ecosystem that combines virtual realities, advanced simulations and the connection between digital and physical systems. This development presents unprecedented opportunities to optimize port planning, operation and sustainability, marking a new era in logistics management and in the interaction of key actors in the supply chain. In this context, a central question guides the research: **How can virtual universes transform the operation, management and collaboration in ports, promoting greater sustainability and global competitiveness?**

The answer to this question requires a thorough analysis that not only assesses the potential impact of the metaverse on port systems, but also identifies the challenges associated with its implementation. The metaverse is presented as a three-dimensional digital environment that can replicate and optimize port operations through advanced tools such as digital twins, real-time simulations, and augmented reality. In addition, its integration with technologies such as blockchain can guarantee transparency and security in data management. This research aims to explore how these capabilities can transform ports into more efficient and sustainable logistics hubs, capable of meeting the challenges of global trade.

The overall goal of this analysis is to understand how the metaverse can be integrated into port systems to optimize their operations, improve environmental sustainability, and foster collaboration among the various actors involved. This approach seeks to address the complexities of port digitalization from a holistic perspective, considering both the benefits and barriers that could arise during the implementation process.

To achieve this main goal, several specific goals are set that address the different dimensions of metaverse integration in ports. First, it seeks to assess the current state of technological readiness of ports to adopt this technology. This involves analyzing factors such as the existing infrastructure, the level of digitalization, and the interoperability between technology systems. This initial analysis is crucial to identify the technology gaps that need to be closed to facilitate a smooth transition to the use of the metaverse.

In addition, it is proposed to identify the key applications of the metaverse in the port environment, considering practical use cases that can generate tangible benefits. For example, digital twins make it possible to virtually replicate port operations, offering a tool to simulate maritime traffic flows, optimize berthing scheduling, and minimize downtime. These simulations can also be used to train operators in virtual environments, improving safety and reducing costs associated with operational errors. In this context, augmented reality also plays an important role in facilitating the visualization of critical data in real time and improving decision-making in complex operations.

The third objective focuses on exploring the socioeconomic and environmental benefits that the metaverse can bring to ports. From an economic perspective, optimizing processes through real-time simulations can reduce operating costs and increase logistics efficiency. From an environmental standpoint, the adoption of the metaverse can contribute to sustainability by minimizing carbon emissions through more efficient route planning and electrification of port infrastructure. These benefits not only positively impact port operations, but also strengthen ports' commitment to the Sustainable Development Goals (SDGs).

A fourth key objective is to develop a strategic framework for the adoption of the metaverse in ports. This framework should address fundamental challenges such as resistance to organizational change, technological interoperability, and staff training. The transition to the use of the metaverse not only requires investment in technological infrastructure, but also a cultural transformation within port organizations. This involves training workers in the use of advanced technologies and fostering an innovation mindset that embraces change as an opportunity to improve.

Finally, it seeks to design metrics that allow the impact of the metaverse on ports to be measured. These metrics are essential for evaluating the success of digitization initiatives and for adjusting strategies as needed. Key indicators such as reducing operating costs, improving environmental sustainability, and increasing logistics efficiency provide a basis for measuring progress and ensuring that the benefits of the metaverse are tangible and sustainable in the long term.

In addition to the objectives, this research is based on three main hypotheses that structure the analysis and guide expectations about the impact of the metaverse on ports. The first hypothesis states that the adoption of the metaverse, including technologies such as digital twins, augmented reality, and blockchain, significantly improves the operational efficiency and sustainability of ports. This assumption is based on the metaverse's ability to optimize processes, reduce downtime, and improve strategic planning through advanced simulations.

The second hypothesis suggests that ports that integrate the metaverse into their planning and operation strategies will gain competitive advantages over those that do not. These benefits include streamlined logistics processes, reduced operating costs, and a greater ability to adapt to changes in global trade. In addition, the metaverse can improve collaboration between different actors in the logistics chain, facilitating coordination and decision-making in real time.

Finally, the third hypothesis identifies the main challenges for the implementation of the metaverse in ports. These challenges include a lack of interoperability between technology systems, limited technological knowledge of staff, and concerns around cybersecurity. Addressing these barriers requires a strategic approach that combines infrastructure investment with robust training programs and security measures.

In short, the metaverse represents a unique opportunity to transform ports into more efficient, sustainable, and interconnected logistics hubs. However, its implementation requires careful planning, strategic investment, and a commitment to innovation. This research not only seeks to answer fundamental questions about the impact of the metaverse, but also to provide practical solutions that allow ports to lead the transition to a digitized future. With a clear strategy and a collaborative approach, the metaverse can become a key driver for the sustainability and global competitiveness of ports in the 21st century.

- **RQ4. How will the application of the ETS affect European ports, reconfiguring the economic, operational and environmental dynamics of the maritime sector?**

The European Union's Emissions Trading System (ETS) marks a transformative milestone on the road to climate neutrality, especially for the maritime sector, which plays a central role in global trade. The research question guiding this analysis is: **How will the application of the ETS affect European ports, reconfiguring the economic, operational and environmental dynamics of the maritime sector?** This issue encompasses a broad perspective that seeks to assess the multifaceted impacts of the ETS, while identifying the critical opportunities and challenges it poses.

At its core, the ETS introduces a market-based mechanism to reduce greenhouse gas emissions, obliging industries, including shipping, to acquire permits for every tonne of CO_2 emitted. This approach not only incentivises cleaner technologies and practices, but is also aligned with the European Green Deal's ambition to reach net-zero emissions by 2050. In this context, the study analyses the implications of the ETS on European ports, focusing on three key dimensions: economic competitiveness, sustainability and regulatory adaptation.

The general objective of this research is to assess the economic impact of the ETS on European ports, placing particular emphasis on its influence on trade routes, port competitiveness and the environmental footprint of the maritime sector. This analysis is crucial to understanding how the ETS can drive structural changes in the shipping industry and port operations.

The specific objectives provide a more detailed approach to examining the effects of ETS. The first focuses on identifying the economic implications for shipping companies operating within the ETS framework. By analysing variables such as emission permit costs and necessary operational adjustments, the research assesses how these factors might influence route selection, load distribution and port infrastructure investment decisions.

Another critical goal is to explore the phenomenon of carbon leakage, where stricter regulations in European ports could divert maritime activities to regions with less stringent emissions controls. This unintended consequence represents a significant risk to the effectiveness of the ETS, as it could undermine global emission reduction targets while weakening the competitiveness of European ports. Understanding the mechanisms and indicators of this carbon leakage is essential to developing mitigation strategies.

In addition, the study seeks to assess the opportunities for innovation and adoption of green technologies that the ETS could stimulate. Financial pressures stemming from emissions costs can act as a catalyst for shipping companies and ports to invest in alternative fuels, energy-efficient technologies and digital solutions. These advances not only align with sustainability goals, but also strengthen long-term competitiveness.

Finally, the research addresses the broader socioeconomic impacts of the ETS, particularly on port-dependent communities. Changes in maritime traffic, alterations in logistics patterns and possible job losses are among the consequences that could have an impact on local economies. This dimension underscores the importance of balancing environmental goals with economic resilience and social equity.

The study is based on three main hypotheses that reflect the key aspects of the impact of the ETS. The first hypothesis is that the ETS will impose significant economic costs on European ports, which could reduce their competitiveness in the global shipping market. This assumption is based on the expectation that higher operating costs arising from emission permits could discourage shipping companies from using European ports, redirecting traffic to other hubs outside the EU.

The second scenario suggests that the ETS will accelerate the adoption of green technologies and sustainable practices in the maritime sector. By creating a financial incentive for emissions reductions, the system could boost innovation in areas such as alternative fuels, renewable energy integration, and process digitalization. This transformation could position European ports as leaders in sustainable maritime operations.

The third scenario addresses the challenges related to regulatory adaptation and international coordination. Implementing the ETS requires strong governance structures, effective compliance mechanisms, and harmonious integration with global maritime policies. Without these elements, the system risks fragmenting the regulatory landscape and exacerbating disparities between regions.

To explore these hypotheses, the research employs a comprehensive methodology that combines literature review, expert consultations, and scenario analysis. The use of Ishikawa diagrams facilitates the identification of key factors influencing the implementation of the ETS, from technological and economic considerations to regulatory and social dimensions. Maritime scenario simulations shed light on the potential responses of shipping companies and ports to the ETS, providing valuable insights into future trends.

Preliminary findings reveal a complex interplay of challenges and opportunities. On the one hand, the ETS introduces significant costs that could jeopardize the financial viability of some European ports, especially those facing competition from non-EU hubs. On the other hand, the system provides a clear impetus towards innovation and sustainability, with the potential to transform the maritime sector into a key pillar of the European Green Deal.

The implications of these findings transcend the maritime sphere. By reshaping trade routes, logistics patterns, and investment priorities, ETS has the potential to influence global supply chains and economic networks. This interconnectedness underscores the importance of taking a holistic approach in policy design and implementation, ensuring that the ETS achieves its environmental objectives without compromising economic stability or social cohesion.

In conclusion, the ETS represents both a challenge and an opportunity for European ports and the maritime sector in general. While the system introduces new complexities and costs, it also paves the way for transformative change and sustainable growth. By addressing the challenges identified and seizing the opportunities, European ports can successfully navigate this transition, setting a benchmark for the global maritime community in the fight against climate change.

- **RQ5. How can Bayesian networks help assess the sustainability of the marine renewable energy sector in Spanish ports, enabling better strategic decision-making?**

The integration of marine renewable energies in Spanish ports, as part of the Blue Economy, represents an essential strategy to move towards sustainable development that balances the economic, social and environmental dimensions. This approach is crucial to meet the challenges of the energy transition and achieve the climate objectives set by the European Union in initiatives such as the European Green Deal and the "Fit for 55" programme. In this context, the research raises a central question: **How can Bayesian networks help assess the sustainability of the marine renewable energy sector in Spanish ports, enabling better strategic decision-making?**

The Blue Economy, based on the sustainable exploitation of marine resources, identifies renewable energies as a key sector to promote economic growth and reduce dependence on fossil fuels. This study takes an innovative approach by using Bayesian networks to analyse the most relevant sustainability indicators in 28 Spanish port authorities. The methodology focuses on identifying interdependent relationships between economic, social and environmental factors, providing a comprehensive vision for strategic planning and resource optimization.

The general objective of this research is to identify the key indicators that drive the sustainable development of the marine renewable energy sector in Spanish ports. This includes assessing how factors such as economic investments, environmental characterization and occupational safety influence the sustainability of the sector. In addition, it seeks to develop a support tool for decision-making based on Bayesian networks, which facilitates a balanced management of resources and prioritizes investments in critical areas.

Among the specific objectives are the selection of relevant indicators, the creation of a robust database and the development of a Bayesian model to represent the relationships between variables. For example, indicators such as the evolution of investments in port infrastructures, the percentage of expenditure on environmental characterization and the rate of annual occupational accidents were identified as critical variables. These data not only reflect the current state of the sector, but also allow us to predict the effects of different investment and regulatory strategies.

Bayesian networks offer a significant advantage in this analysis, as they allow complex systems to be modeled and uncertainty in strategic decisions to be managed. In analyzing the results, seven main indicators were identified that highlight the importance of economic and environmental investments, as well as occupational safety measures. Investment in port infrastructure, for example, is critical to ensure the integration of renewable technologies such as offshore wind. Similarly, environmental characterization ensures that renewable energy projects minimize their impact on marine ecosystems, promoting a balance between economic development and environmental conservation.

Another relevant finding is the relevance of occupational safety in the development of the sector. The frequency rate of occupational accidents was identified as a key indicator that underlines the need to adopt measures that guarantee the safety of workers involved in offshore renewable energy projects. This not only contributes to social well-being, but also strengthens operational sustainability and reduces risks associated with project disruptions.

The analysis also reveals significant challenges, such as the lack of homogeneity in the data and the need to improve coordination between different port authorities. However, Bayesian networks proved to be effective tools for simplifying complex models, prioritizing relevant connections between variables, and facilitating clear interpretations for decision-making. This approach allows port managers to identify critical areas of intervention and optimize resources to maximize the positive impact of the sector in economic, social and environmental terms.

At the strategic level, this study underlines the importance of integrating sustainability into all stages of the sector's development. This includes fostering collaboration between key actors, such as governments, businesses, and local communities, and adopting policies that promote the use of clean technologies and responsible practices. In addition, the need to establish clear metrics to assess progress towards sustainability goals is emphasized, ensuring that investments generate tangible and lasting benefits.

In conclusion, the use of Bayesian networks to assess the sustainability of the marine renewable energy sector offers an innovative and practical perspective to address the challenges of the energy transition in Spanish ports. This approach not only facilitates more informed decision-making, but also reinforces the role of ports as engines of the Blue Economy and agents of change towards a more sustainable and resilient future. By integrating economic investments, environmental management and occupational safety, ports can position themselves as leaders in the transition to a low-carbon economy, contributing significantly to the sustainable development of coastal regions and the fulfilment of global climate commitments.

3. METHODOLOGY

Chapter 3 describes the methodology used in this research, based on a mixed approach that integrates qualitative and quantitative methods to analyse port sustainability, the Blue Economy and digitalisation in Spanish ports. The methodological tools used, such as the Delphi method, affinity and Ishikawa diagrams, Bayesian networks and the End-to-End tool, are presented, highlighting their role in data collection and analysis, identification of causal relationships and evaluation of scenarios. In addition, the design of the research is detailed, structured in three interrelated blocks: Blue Economy, Emerging Technologies and Case Studies towards Sustainable Ports. This comprehensive approach allows the objectives of the thesis to be systematically addressed, providing a robust framework for strategic decision-making in the port field.

3.1. Methodological tools

The design of this research is based on a mixed approach that integrates qualitative and quantitative methods, which allows to address the complexity inherent in the evaluation of sustainability, digitalization and the implementation of innovative technologies in Spanish ports. This approach offers a comprehensive perspective by combining in-depth and subjective expert analysis with quantitative models that facilitate the interpretation and prediction of patterns in complex systems. The use of complementary methodological tools, such as the Delphi method, Bayesian networks, affinity diagrams and end-to-end tools, guarantees a rigorous analytical process and oriented towards decision-making.

The choice of the mixed approach is justified by the need to capture both the objective and subjective dimensions of the phenomenon under study. On the one hand, qualitative methods make it possible to understand the perceptions, experiences and opinions of experts in the field, which is crucial for defining key indicators and establishing meaningful connections between variables. On the other hand, quantitative methods, such as the use of Bayesian networks, provide a structured framework for analyzing causal relationships and evaluating potential scenarios based on empirical data. This methodological integration is particularly suitable for applied research in complex and multidimensional contexts such as ports.

The **Delphi method** is one of the qualitative tools used in this research to collect and validate expert information. This approach consists of a series of structured consultation rounds to a panel of experts in areas related to port sustainability, the blue economy and digitalisation [46]. Each round allows the group's opinions to be refined and consolidated, achieving a consensus on the key indicators and the most relevant variables to be included in the analysis model.

The use of the Delphi method is essential to guarantee the validity and relevance of the selected indicators, since it integrates the practical experience and academic knowledge of the participants. In addition, this process encourages a collaborative and participatory approach, ensuring that methodological decisions reflect the realities and challenges of the port sector.

The **End-to-End tool** is an innovative and comprehensive methodology, designed to evaluate, manage and optimize complex systems from inception to completion. Specifically adapted to the maritime-port sector, this tool offers a structured framework for analysing the different aspects involved in ports [8]. Covering all phases of a system's lifecycle, from data collection and historical analysis to future scenario modeling and strategic decision-making, this tool provides a comprehensive and effective approach.

In the context of digital port governance, the End-to-End tool responds to the growing need to improve efficiency, transparency and sustainability. It facilitates the collection of data from various sources, allows for in-depth analysis of operational processes, and assesses end-user satisfaction levels. In addition, its intuitive interface allows stakeholders to visualize the results and make evidence-based strategic decisions. This flexibility makes the tool a key element in identifying inefficiencies, detecting bottlenecks and proposing actionable solutions that optimise port competitiveness.

The versatility of the tool goes beyond diagnosis, as it also allows future trends to be projected and digital governance strategies to be aligned with global technological advances. By integrating historical knowledge with current data, the tool not only assesses the current state of digitalization in ports, but also establishes a roadmap for continuous improvement.

Affinity diagrams are employed as a qualitative tool to organize and categorize the information collected during the Delphi process. This technique facilitates the identification of patterns and connections between related ideas, which helps to structure the database of key indicators and to conceptualize the main dimensions of the analysis model [47].

For example, during meetings, experts can propose a wide range of indicators and variables. Affinity diagrams allow these elements to be grouped into consistent categories, such as environmental sustainability, operational efficiency, and economic development. This organization facilitates the development of a clear conceptual framework and guides subsequent phases of modeling and analysis.

The use of **Ishikawa's diagrams** in this research is critical to identify and analyze the root causes of sustainability-related issues in ports [48]. These tools allow complex problems to be broken down into manageable dimensions, organizing the causes into key categories such as economic, social, technological, and environmental. For example, in the case of low adoption of digital technologies, the diagram can identify barriers such as lack of technological interoperability, high investment costs, resistance to change, and regulatory gaps. This structure makes it easier to prioritize critical areas of intervention and guide solution strategies.

Bayesian networks constitute the core of the quantitative analysis of this research. These tools allow complex systems to be modeled by identifying causal relationships between variables and managing the uncertainty inherent in the available data [49]. In the context of ports, Bayesian networks are particularly useful for assessing how different economic, social and environmental factors interact to influence sustainability and technological development.

For example, network nodes can represent variables such as infrastructure investments, the frequency of workplace accidents, or the environmental impact of port operations. The connections between these nodes reflect causal relationships based on empirical data and expert opinions, which makes it possible to simulate scenarios and predict the effects of different strategic decisions. This predictive capability is essential to inform the planning and prioritization of interventions in ports.

The mixed approach adopted in this research reflects the complexity and multidimensionality of the phenomenon studied. By combining qualitative tools such as the Delphi method, the Ishikawa diagram, and affinity diagrams with quantitative models based on Bayesian networks, the methodological design allows critical research questions to be addressed from multiple perspectives. This approach not only enriches the understanding of the topic, but also provides a solid basis for strategic decision-making that promotes the sustainable and technological development of ports in the context of the blue economy and energy transition.

3.2. Research Design

The schematic diagram of the thesis represents in a structured and concise way the three main blocks that articulate the research: *Blue Economy*, *Emerging Technologies* and *Case Studies towards Sustainable Ports* (Figure 3.1). Each block reflects a different, but complementary, approach to analysing sustainability and digitalisation in Spanish ports, linking objectives, methodologies, tools and results.

Block 1: Blue Economy

This first block establishes the conceptual framework of the *Blue Economy* as a fundamental pillar in port sustainability. It focuses on assessing the level of development of the established and emerging dimensions of the Blue Economy within the Spanish port system. To this end, the methodological design is based on the use of the Delphi panel and the construction of a specific evaluation indicator.

The Delphi panel allows the collection and consolidation of the opinions of experts in port sustainability and the Blue Economy, identifying the key indicators that best represent the current state and the prospects for the development of this economic model. The information obtained is used to develop an evaluation tool capable of classifying Spanish ports in terms of their implementation of the Blue Economy, offering a ranking that is broken down into global and specific results by dimensions. This provides a clear view of the current landscape, and facilitates the identification of gaps and opportunities for improvement in port sustainability.

The results obtained highlight both the established dimensions, such as maritime transport and coastal tourism, and the emerging dimensions, such as marine renewable energies and biotechnology. This block serves as a conceptual basis for the rest of the research, as it provides a theoretical and methodological framework that can be replicated in future studies, as well as a reference for strategic decision-making in ports.

Block 2: Emerging Technologies

The second block addresses digitalisation and the impact of *Emerging Technologies* on ports, highlighting their transformative role in terms of sustainability and competitiveness. This block is organized around so-called *virtual ecosystems*, which include tools and approaches such as digital governance, digital twins, the metaverse, and the digitalization of the hinterland. Each of these aspects is addressed through specific methodologies that allow their adoption and effectiveness in ports to be analyzed.

The first subcategory of this block uses affinity diagrams to identify and categorize the key elements needed for the implementation of these technologies. This approach, based on panels of experts, is developed in two phases. In the first, the essential elements related to technological implementation are identified. In the second, weights and priorities are assigned to the categories and subcategories identified, offering a clear and well-founded hierarchy that guides decision-making. This process allows for the establishment of a framework to guide the strategic adoption of technologies in ports.

The second subcategory focuses on the use of the End-to-End tool, designed to analyse digital governance in Mediterranean ports. This tool provides a comprehensive approach ranging from data collection to generating actionable results, assessing the ability of ports to manage digital data and operational processes efficiently. The results obtained include a ranking of ports according to their level of digital governance. This analysis allows us to identify both strengths and weaknesses in the adoption of digital technologies, offering concrete proposals to optimize efficiency and operational sustainability.

Block 3: Case Studies towards Sustainable Ports

The third block focuses on specific applications of innovative methodologies to measure impacts and support strategic decision-making in the port context. This block includes two different lines of research.

The first line assesses the impact *of the Emissions Trading System (ETS)* on European ports. Using Ishikawa diagrams and economic impact calculations, this line analyzes the causes and consequences of regulatory measures in economic, social, and environmental terms. This approach makes it possible to identify the main challenges associated with the ETS, such as carbon leakage, and to prioritise areas of intervention that maximise sustainable benefits. The results include a comparison of the dimensions of environmental, economic and social sustainability, providing a holistic view of the impact of the ETS.

The second line of research uses Bayesian networks to assess the dimension of marine renewable energies in Spanish ports. This methodology makes it possible to model causal relationships between key variables, such as infrastructure investments and occupational safety, and to analyse future scenarios. The results include the identification of priority indicators to foster the development of this sector and the creation of a decision support tool, designed to guide sustainable strategies in ports.

Connecting Blocks

The diagram reflects how the three blocks are interconnected, combining theoretical and applied elements to offer a comprehensive vision of port sustainability and digitalisation. While the Blue Economy and Emerging Technologies blocks lay the conceptual and methodological foundations, the Case Study block applies these approaches to address specific issues and generate practical recommendations. Overall, the diagram illustrates a structured and multidimensional approach to addressing the challenges and opportunities of the port sector in the context of the energy transition and the Blue Economy.

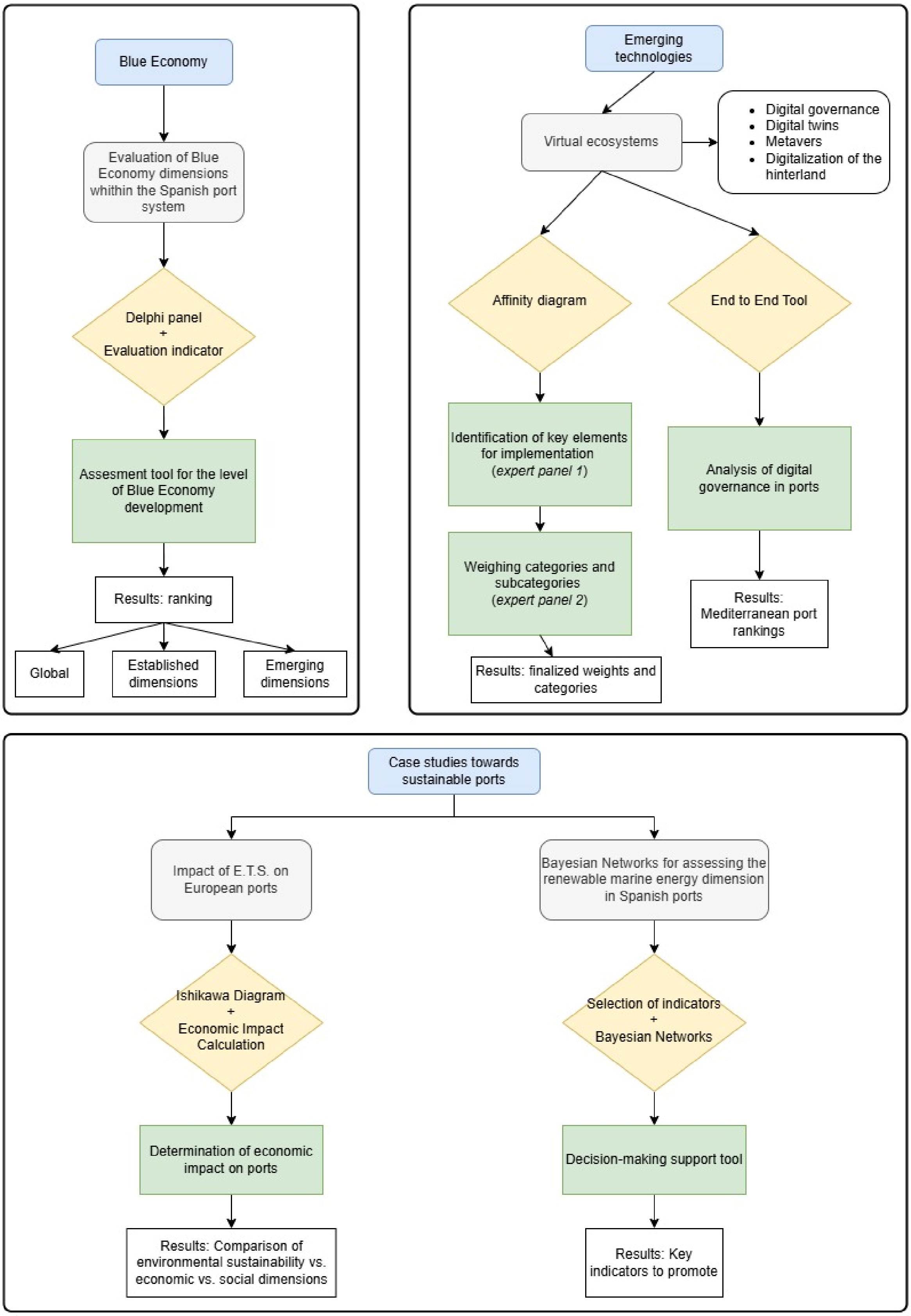


Figure 3.1: Conceptual framework of the research. Source: Own elaboration

PART II:
DEVELOPMENT AND RESULTS

4. THE BLUE ECONOMY IN SPANISH PORTS SYSTEMS

This chapter presents the accepted manuscript of RA1 that has been published in a peer-reviewed and indexed journal:

Vaca Cabrero, J., Gómez Garach, C. P., Camarero Orive, A., & González-Cancelas, N. (2024). **Evaluation of the Implementation of the Dimensions of the Blue Economy in Spanish Ports**. *Journal of Marine Science and Engineering*, *12*(2), 222. https://doi.org/10.3390/jmse12020222.

Abstract: The Blue Economy is a relatively new concept. In 2010, Günter Pauli coined this term to refer to an economic development using as an example the cycles of the natural world, where a waste is raw material for a process. Currently, the Blue Economy is a much broader and more transversal concept and strongly related to maritime economic sectors, from maritime transport to off-shore renewable energies through port operations. In short, the Blue Economy encompasses classic sectors such as shipbuilding together with more innovative concepts in the ports, such as digitalisation, innovation or energy transition. In this research, a new tool is developed through which, as its main objective, it allows to obtain a degree of implementation of the dimensions of the Blue Economy in Spanish ports through the evaluation of each of the economic sectors that constitute the B.E. in the 28 Spanish port authorities. To this end, a Delphi panel has been used to determine the importance of each economic dimension, a database has also been generated to know the state of development of these dimensions in each port and some equations have been developed to determine in base 100 how developed each port is.The results obtained show a notable development in the average of Spanish ports, highlighting Las Palmas as the port that has most developed the Blue Economy.

Keywords: B.E., Grade development tool, Spanish ports.

4.1. Introduction

The origin of the Blue Economy (B.E.) is based on the generation of wealth and economic growth, promoting the regeneration and preservation of ecosystems, through the use of the resources provided by the marine environment. This new economic model seeks to mimic the functioning of the natural ecosystem. It aims to implement the principle of the circular economy that seeks to convert waste into newly usable resources, something that allows the marine ecosystem to be considered as a source of innovation and growth for profitable and sustainable development [9].

Today, when experts talk about the B.E., they do so from a more transversal perspective, closely related to the maritime economic sector [50].

The B.E. represents a paradigm shift in economic thinking, where the sustainable use of ocean resources and services takes center stage, recognizes the importance of marine resources and ecosystem services in driving their development, while emphasizing the need for responsible resource management and environmental conservation [14]. It encompasses a variety of sectors, including fisheries, aquaculture, renewable energy, coastal tourism, marine biotechnology, and shipping, among others. By taking a holistic approach to resource management, the B.E. in the context of port development, seeks to strike a balance between economic growth, social well-being and environmental sustainability [51]. According to the European Union, the development of this economic model is closely linked to the concept of Blue Growth Initiative is associated with a long-term initiative to support the sustainable development of the marine and maritime sectors [52].

As can be seen, the concept of B.E. is relatively recent compared to other traditional economic approaches. Although the oceans have always been a source of resources and economic activity, the term "B.E." and its specific focus began to gain prominence from the 2010s onwards highlighted by the report of the European Parlament [10], a key milestone that drove the popularisation of the term. Since then, the concept of the B.E. has been adopted and scaled up by various international organizations, national governments, academic institutions, and interest groups [12]. It has become a strategic approach to address sustainability challenges in relation to oceans and related economic activities.

At present, there is almost no research or methods that allow the establishment of specific criteria to assess the level of development or progress of this B.E. model, with even more research directly related to port activity.

Thus, the core of the research is to create a model for evaluating the degree of implementation of the different sectors of the B.E. in Spanish ports through different tools such as the creation of a database to collect the different projects carried out by the 28 Spanish Port Authorities. Using a Delphi panel to assess the degree of importance of each economic sector involved and create a method to the B.E. in each Port Authority.

4.2. State of the art

The B.E. has emerged as a key concept in the field of sustainability and economic development. In the definition and presentation of this term, it is essential to talk about the figure of the Belgian economist, Gunter Pauli According to Pauli, this economic model seeks to enhance sustainability, guaranteeing the improvement of the system and promoting the emergence of new possibilities that allow future generations to have, at least, the resources that the current generation has today. It turns scarcity into abundance, and poverty into development, working with what you have, being creative and encouraging entrepreneurs to make this possible. These are some of the principles that lay the foundations of the B.E., where it is worth highlighting the discrepancy between those who found this aforementioned economy and the principles of the linear economy [9].

Over the years, the concept of B.E. has evolved and expanded across different sectors and regions.

The evolution of the concept of the B.E. has been a gradual process that has gained momentum in recent decades by linking up with the marine and maritime economic sectors. Initially, it focused on traditional economic activities such as fishing, coastal tourism, and boating. However, with the growing recognition of the importance of marine resources and the need for their sustainable management, the concept has expanded to include other sectors, such as marine renewable energy, marine biotechnology, sustainable aquaculture, shipping, port activities, and the responsible exploration and exploitation of marine mineral and energy resources [12] [53]. In addition, the B.E. approach has been expanded to cover aspects such as maritime governance, maritime security and integrated coastal zone management. [54]. Numerous institutions have given significant importance to this economic model, and in recent years this term has become popular among different administrations and organizations such as the governments that make up the countries, institutions such as the EU, the United Nations, FAO, etc. [55].

In the European context, the European Union (EU) annually issues a report entitled Blue Economy Report [53], 2021 as a sign that the B.E. has become a priority on the policy agenda. The European Commission has identified 14 main sectors of the B.E., which are divided into two main groups: established sectors and emerging sectors.

The established sectors are those that already have a relevant track record as well as a more advanced degree of development than others, being contributors to the evolution of the B.E. within the European Union. A total of seven are distinguished, which in turn are divided into different subsectors. (Figure 4.1)

Figure 4.1: Established sectors of the B.E. Source: Own elaboration based on the Blue Economy Report of the European Union.

Emerging sectors are defined as those sectors that are novel in the field of the B.E., referring to those activities that are directly linked to the marine environment whose environment has not reached a certain degree of maturity or where data are not available in the public domain (Figure 4.2).

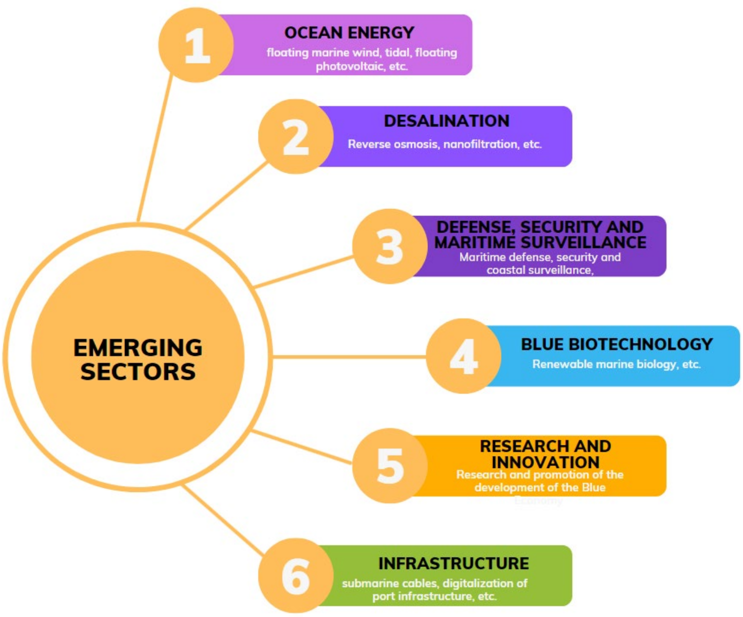


Figure 4.2: Emerging sectors of the B.E. Source: Own elaboration based on the Blue Economy Report of the European Union.

These sectors, both established and emerging, have significant potential to generate jobs, economic growth and sustainable development in Europe's coastal regions. The EU has developed specific strategies and policies to foster the growth of these sectors, such as the Sustainable B.E. Action Plan and the Marine Strategy Framework Directive [56].

Linking the B.E. to the Sustainable Development Goals is critical to understanding its importance in the global context. SDGs 14 (Life Below Water) and 15 (Life on Land) are directly related to the conservation and sustainable use of marine and terrestrial resources, respectively. These goals seek to protect marine and terrestrial biodiversity, promote sustainable fisheries, reduce marine pollution, and conserve coastal and marine ecosystems [11].

In addition, the B.E. can also contribute to other SDGs, such as SDG 16 (Peace, Justice and Strong Institutions) and SDG 17 (Partnerships for the Goals). In the case of SDG 16, the B.E. can foster effective maritime governance, the fight against illegal and unregulated fishing, and promote peace and security in the oceans. On the other hand, SDG 17 highlights the importance of partnerships and global cooperation to achieve the Sustainable Development Goals, and the B.E. can facilitate collaboration between different actors, including governments, international organizations, the private sector and civil society [11].

It is well known that the B.E. requires financing for its implementation, development and flowering. It needs the help of partnerships along with public-private partnerships. However, it is true that a conditioning factor is the degree of economic development of each country. Sectors that are deeply linked to the port sector, such as fishing or aquaculture, and with an important weight in the B.E., require reforms and stimuli that promote their growth or renewal. Fiscal policy is used in this type of case to encourage sustainable development by encompassing: environment, economy and social collective. [57]. One of the main investors in this area of the economy is the World Bank, which has invested more than $9 billion in active projects since 2021. It is worth highlighting programs such as "Problue" born in 2018, which is a trust fund, composed of numerous donors that supports the development of the marine environment and the resources that are intrinsically linked to it [58]. Financial instruments such as bonds are also used with the aim of promoting new models of sustainable financing. Green and blue bonds are debt issues that aim to finance projects focused on conserving and protecting the environment and the marine environment, respectively. FAO. (2020). [59].

Ports have a fundamental possition in this economy through the different sectors [60]. There is a growing interest in taking advantage of the resources and opportunities offered by port areas. Ports are not only key infrastructures for international trade, but they can also become hubs for innovation and development of sustainable technologies. For example, measures are being implemented to reduce marine pollution in ports, such as the electrification of cargo handling equipment and the use of cleaner fuels. In addition, new ways of harnessing ocean energy and marine mineral resources in ports are being explored, thus promoting the transition to a more sustainable B.E. [61].

Regarding the development of the B.E. in Spain, there are several reports and studies that highlight its importance and potential. According to a report by the Cotec Foundation, Spain has a large industrial and technological base related to the marine environment, which gives it an advantageous position. The report also highlights the need to boost research, development and innovation in this area, as well as to promote collaboration between the public and private sectors.

Another relevant report is spanish sustainable development strategy [62], prepared by the Ministerio de Transición Ecológica. This plan establishes a roadmap to promote the sustainable growth of the B.E. in the country, addressing aspects such as the protection of the marine environment, the promotion of sustainable fisheries, the promotion of aquaculture, the improvement of maritime governance and the creation of employment in related sectors.

Port authorities in Spain are no strangers to this transformation that the development of the B.E. entails, there are experiences that corroborate it:

The Port of Vigo has been developing the "Blue Growth" strategy for a few years, which aims to make this port an inclusive, innovative, connected and green port, with the deadline for achieving it being 2027 [63]. The Port of Barcelona has a great involvement with the B.E. and has "Blue-Up", a program which has been designed through a public-private collaboration, which encourages the participation of sustainable and blue start-ups in order to promote the progress and development of their initiatives more quickly. The port of Castellón promotes projects linked to blue energy, and emerging sectors such as the repair, construction, maintenance or remodelling of ships [16].

On the other hand, P. Bond [64] provides a critical assessment of the implementation of the B.E. in South Africa, highlighting the threats, contradictions and resistances that arise in the process, and offers a perspective from the field of political ecology.

P. Choudhary *et al* [15] examines the potential of the B.E. as a way to empower undervalued marine ecosystems and turn them into a sustainable industry that promotes economic development and conservation of marine resources. It provides a perspective on how the B.E. can contribute positively to the management of marine ecosystems and the creation of a sustainable industry.

In the study prepared by R. M. Martínez-Vázquez et al. [65], the authors provide a quantitative assessment of the impact of B.E. sectors using a variety of statistical approaches. The results could help to better understand how these economic activities influence various aspects, which could be valuable for decision-making and policy planning related to the B.E. and the sustainable management of marine resources.

E. Tijan et al. [3] examines how the adoption of digital technologies in the shipping sector can be an effective means of achieving the objectives of the B.E. by improving sustainability, efficiency and economic growth in the maritime domain.

Another international example is the case of Montenegro and its maritime transport within the framework of the B.E. [66]. It provides a detailed analysis of the measures and strategies implemented in Montenegro to promote more sustainable shipping practices and their impact in the context of the B.E.

B.E. is an evolving concept. It is closely linked to concepts such as digitalization, energy transition and blue ocean.

There are both established and emerging sectors (maritime transport, port activities, research and innovation, blue biotechnology, etc.) that are currently experiencing a digital revolution. New technologies such as Artificial Intelligence, Digital Twins and Blockchain are helping in the decision-making of the different agents involved in the infrastructure, facilitating the visualization of information, real-time collaboration, capacity management and planning, etc. [18], [19].

Spanish ports are implementing these new technologies to promote sustainability, environmental quality and logistics efficiency. This digital transformation is known as Ports 4.0 or Smart Ports, and encompasses aspects such as automation, digitization, interoperability, and improving the customer experience. The Blue

Ocean concept aims to achieve effective digitalisation that will lead the Spanish port system towards Port 4.0 [23].

Other sectors such as Marine Renovable energy or ocean energy are key activities in ports to achieve the energy transition. Ports are energy hubs, through which most of the energy materials used by coastal countries are imported and exported [67]. Mills for offshore wind farms are also installed and distributed in port facilities, plants are built to produce green hydrogen, ammonia, etc. Key products to achieve the decarbonisation targets that are being demanded by some national and supranational organisations [68].

This energy transition is not only taking place in the economic sectors associated with a port. The concept of "green port" is becoming more and more widespread and refers to a port that has actively committed to adopting sustainable practices and policies to minimize its environmental impact and promote social responsibility. These ports seek to integrate environmental considerations into their infrastructure and operations, focusing on energy efficiency, emission reduction, waste management, and the promotion of environmentally friendly practices [8].

4.3. Materials and Methods

Objetive

As we have seen in the previous section (state of the art), the B.E. is a innovative term that has not yet had a fully established development of its activity in all the areas it affects. In addition, this term applied in the port area has little experience, i.e. the information is not abundant due to the fact that the activities are relatively recent and it is currently in full implementation and development. There is not a large amount of research on the B.E. applied to ports, nor methods that allow the establishment of specific criteria to measure and/or evaluate the level of development or progress of this economic model.

That is why the core of the paper is to determine the current degree of implementation of the B.E. in Spanish ports.

Method

The methodology that has been developed (Figure 4.3) that is based on the following fundamental points:

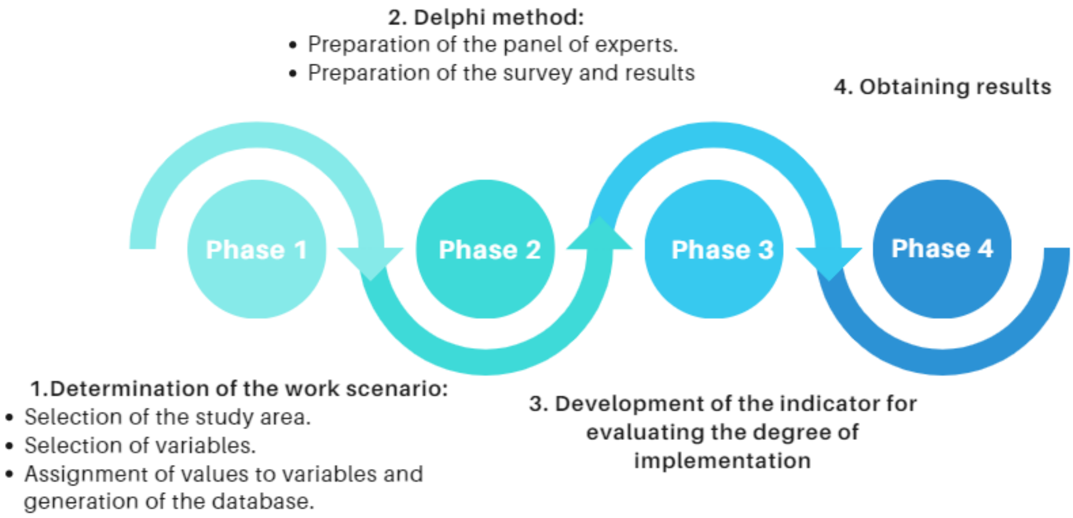


Figure 4.3: Phases of the research. Source: own source

4.3.1. Phase 1. Determination of the work scenario:

Selection of the study area

It has been decided to study the 28 Port Authorities that make up the Spanish Port System. This is due to the fact that Spain is the country in the European Union with the most kilometres of coastline and has access to the two main maritime facades of the European continent, the Atlantic and the Mediterranean. In addition, the Iberian Peninsula has a very important strategic importance because to the south of it is the Strait of Gibraltar, a choke point of international maritime transport routes.

That is why all state-owned ports are considered, as this way a representative sample is obtained.

Below is a map showing the distribution of the locations of the port authorities studied (Figure 4.4)

Figure 4.4: Port Authorities of Spain. Source: Puertos del Estado.

Selection of variables to be studied

According to the literature review carried out in section 2: State of the Art, 7 sectors belong to the group of established sectors and 6 to the group of emerging ones. Each of them has a direct or indirect link with port activities. Table 4.1shows each sector with a short description.

Table 4.1: Classification and description of the sectors of the B.E. Source: own source.

Group	Sector	Description
Established	Living marine resources	It encompasses both the collection of those biological resources with the capacity to degrade and renew themselves (primary sector), as well as their processing (conversion into food, feed, bioproducts and bioenergy), and distribution throughout the supply chain.
	Inert marine resources	Exploitation of energy sources and raw materials from the ocean.
	Marine Renewable Energy	Off-shore wind. Europe is the world leader with 90% of the installed capacity. This sector has experienced exponential growth since 2009 in all indicators, the countries located in northern Europe are the most developed in this sector.
	Port activities	This sector is divided into two main subgroups: loading and storage of goods; and

		maritime and port projects: construction of facilities and service of transport-related activities.
	Shipbuilding and repair	The shipyard industry is a dynamic and competitive sector that Europe leads worldwide.
	Maritime transportation	Composed of the following subsectors: passenger transport, freight transport and transport services.
	Coastal tourism	Largest sector in terms of GDP and jobs. Tourists in the coastal areas of southern European member countries are more numerous, tourism is particularly important in countries such as Spain, Portugal, Italy, Malta and Greece.
Emerging	Ocean Energy	Composed of renewable energies such as: off-shore floating wind, tidal, floating photovoltaic and off-shore H2 generation
	Blue Biotechnology	This sector aims to promote the use of biomass for industrial applications .
	Desalination	This sector will play a major role in the economic development of the continent as many regions of the Mediterranean area will face serious problems of freshwater supply by 2050. The most common technologies in desalination are: reverse osmosis, electrodialysis, nanofiltration and distillation by multi-effect evaporation.
	Defense, Security & Surveillance	A sector of large investments by coastal member countries. In recent years, the European Maritime Security Strategy has been launched, which seeks to protect the citizens and interests of the Union.
	Research & Education	Some destable actions are: ・Knowledge on the impacts of climate change on marine ecosystems. ・Preserve coastal ecosystems. ・Reduce investment risk. ・Development of smart.
	Infrastructure	There are initiatives in ports to reduce emissions during construction and facilitate the colonization of structures. The development of the submarine cable network is also being implemented to improve telecommunications.

Assigning values to variables and developing the database

This phase includes the detailed analysis of all the activities related to the sectors of the B.E. that are being developed in each of the 28 Spanish Port Authorities.

The development of the database comprises two main divisions, the first for established economic sectors and the second for emerging economic sectors. The evaluation criterion used consists of assigning points based on the degree of development or implementation of an economic sector in the Port Authority studied. A maximum score of 3 has been established for those institutions that promote or have implemented the economic activity in question. A value of 2 is assigned to those institutions that are studying the implementation of the aforementioned activity, and finally a score of 1 is given to those that are not adopting measures to implement said activity.

4.3.2. Phase 2. Elaboration of the Delphi panel of experts

In this fourth phase, the aim is to establish the degree of importance of each economic sector studied, for which the Delphi method is used

This method makes it possible to draw up a ranking of importance, and it is also in line with the present level of research, since it is a novel research and there are not too many references on the subject [17].

In the Delphi method there is a dialogue and feedback from experts [46].

The selection of experts from the field of application for the Delphi panel is based on the need to encompass a diversity of perspectives and experiences, thus ensuring a comprehensive representation of knowledge in the area. This large group of experts seeks to reduce individual biases, validate findings, and deepen the exploration of ideas, enriching the panel with a variety of voices and insights. Meaningful expert involvement not only enhances the credibility of the study, but also makes it easier to identify key relationships and gain consensus around the importance of relevant factors in the field of application.

The surveys were carried out electronically using the Microsoft forms platform, this application allows with great agility to send the surveys, collect and analyze the responses and export the data in different formats compatible with different programs to analyze them.

In the selection of experts for the generation of the affinity matrix, rigorous criteria were applied based on professional experience, thematic specialization, diverse representation, previous achievements and contributions, collaborative skills, interdisciplinarity, availability and commitment, as well as recognition in the scientific community. These criteria ensure an equitable and meaningful participation of experts with diverse perspectives and expertise in the field, thereby strengthening the validity and breadth of the analysis in the study. Among the experts are researchers of recognized prestige in the field of port management and operation in Spain, professionals from private companies linked to the economic sectors evaluated such as freight transport companies, handling and storage, etc. Finally, there was also the participation of professionals who have several years of experience working in one of the port authorities.

The questionnaire was answered by 24 experts and consisted of the following questions in which the following results were obtained:

First, ranking the importance of the different Established Economic Sectors that make up the B.E. (Figure 4.5).

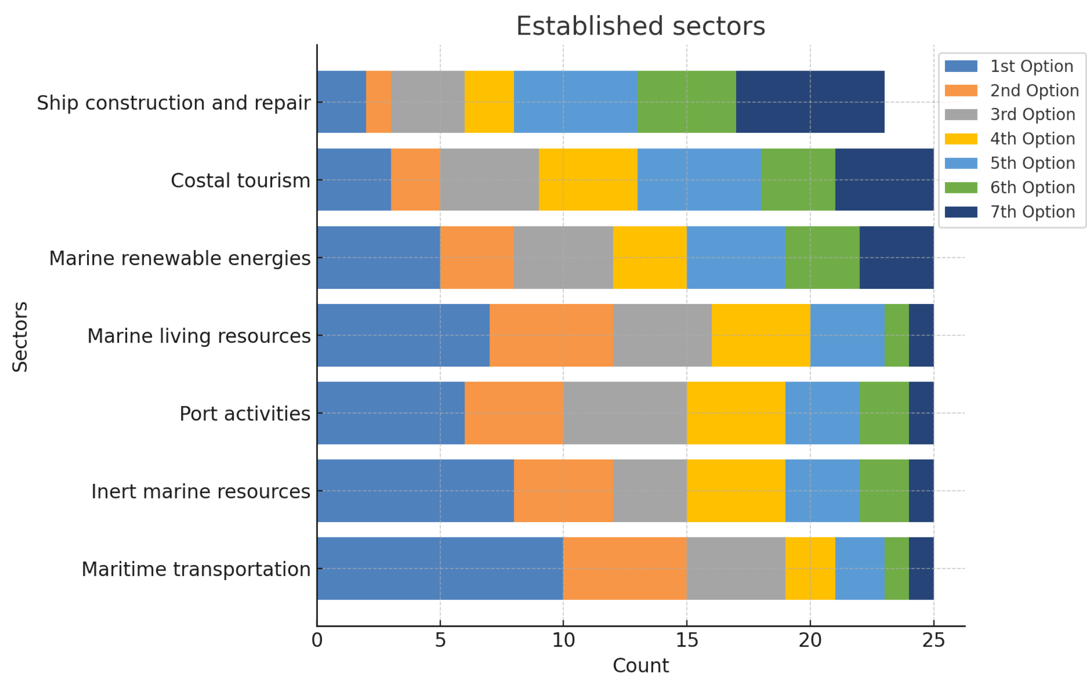


Figure 4.5: Degree of importance of established sectors. Source: own source.

The second question consists of ordering the different emerging economic sectors that make up the B.E. from the most important at least (Figure 4.6).

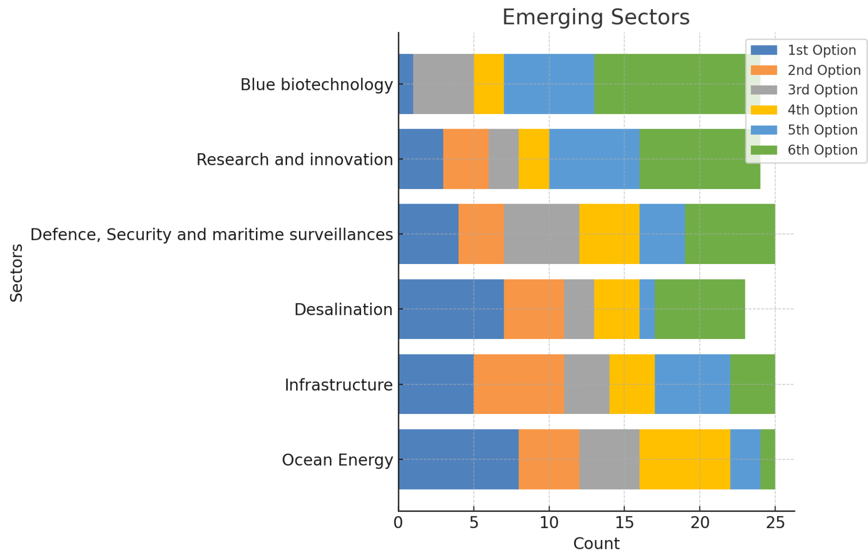


Figure 4.6: Degree of importance of emerging sectors. Source: own source.

The third question asks the respondent to establish a degree of importance on a scale of 1 to 10, according to their own criteria, of the degree of importance that the activities already established have globally (Figure 4.7).

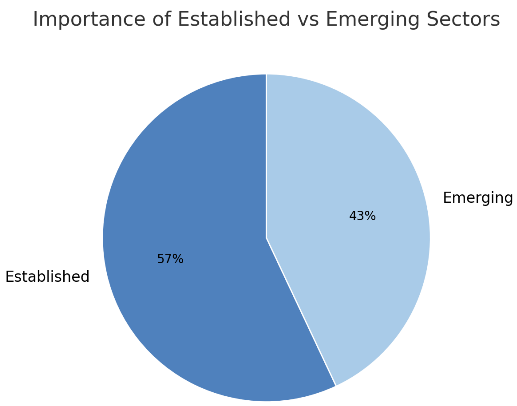


Figure 4.7: Degree of importance of established vs. emerging sectors. Source: own source.

In this way, the importance attributed by the group of experts to the different sectors will be considered with a rounding in order to facilitate calculations, adopting a 60% weight for established activities and, likewise, 40% weight for emerging activities.

4.3.3. Phase 3. Development of the Implementation Assessment Indicator

In this phase of the research, an indicator is developed to asses the B.E. implementation both by economic sectors and by Port Authority.

From the importance rankings obtained from the survey with the Delphi panels of experts, a score is given to each of the sectors evaluated based on the position obtained in the survey (Table 4.2).

Table 4.2: Classification of economic sectors. Source: own source.

Position	Established Sectors	Punctuation	Position	Emerging Sectors	Punctuation
1st	Maritime transportation	7	1st	Ocean Energy	6
2nd	Inert marine resources	6	2nd	Infrastructure	5
3rd	Port activities	5	3rd	Desalination	4
4th	Marine living resources	4	4th	Defence, Security and maritime surveillances	3
5th	Marine renewable energies	3	5th	Research and innovation	2
6th	Costal tourism	2	6th	Blue biotechnology	1
7th	Ship construction and repair	1			

This scale, together with the data obtained in Phase 2, can be used to develop the mathematical expression that will evaluate the degree of development of the B.E.:

Established sectors:

$$R_{ES} = \sum_{i=1}^{m} (\alpha_i \times \beta_i) \times \frac{100}{84}$$

Where:

- R_{ES}: Degree of development of the sectors established for each port authority
- α_i: state of development of the economic sector established in the Port Authority.
- β_i: score according to the importance of the sector obtained using the Delphi method.
- m: each of the seven established sectors of the B.E.
- 100/84: Obtaining results on a base of 100

Emerging Sectors:

$$R_{EM} = \sum_{j=1}^{n} (\alpha_j \times \beta_j) \times \frac{100}{63}$$

Where:

- R_{EM}: Degree of development of emerging sectors for each port authority
- α_j: state of development of the emerging economic sector in the Port Authority.
- β_j: Score according to the importance of the sector obtained using the Delphi method.
- n: each of the six emerging sectors of the B.E.
- 100/63: Obtaining results on a base of 100

The results of the development of the B.E. in each port are obtained by this expression:

$$R_{global} = \left\{ 0.6 \times \left[\sum_{i=1}^{m} (\alpha_i \times \beta_i) \right] + 0.4 \times \left[\sum_{j=1}^{n} (\alpha_j \times \beta_j) \right] \right\} \times \frac{100}{147}$$

The weight is 0.6 for established activities and 0.4 for emerging activities.

4.3.4. Phase 4. Getting results

The results obtained are shown in Table 4.3. This shows for each port authority the degree of implementation of both the established and emerging sectors and their overall result, all based on 100. The last column shows the percentage points of deviation of each port authority from the average of the overall results.

Table 4.3: Degree of implementation of the B.E. in Spanish ports. Source: own source.

PORT AUTHORITIES	ESTABLISHED SECTORS	EMERGING SECTORS	GLOBAL RESULTS	DEVIATION FROM THE MEAN
LAS PALMAS	100	100	100%	21%
BAHÍA DE ALGECIRAS	93	92	93%	13%
HUELVA	93	89	91%	12%
CARTAGENA	90	89	90%	10%

FERROL-SAN CIPRIÁN	90	87	89%	10%
MÁLAGA	90	87	89%	10%
SANTA CRUZ DE TENERIFE	86	87	86%	7%
CEUTA	81	87	83%	4%
A CORUÑA	80	86	82%	3%
ALMERÍA	80	84	82%	2%
BARCELONA	80	84	82%	2%
PASAJES	79	84	81%	1%
VIGO	79	83	80%	1%
ALICANTE	76	79	77%	-2%
AVILÉS	76	79	77%	-2%
BAHÍA DE CÁDIZ	76	78	77%	-3%
BALEARES	76	78	77%	-3%
BILBAO	76	78	77%	-3%
CASTELLÓN	76	78	77%	-3%
MELILLA	76	75	76%	-4%
MOTRIL	76	75	76%	-4%
SANTANDER	76	68	73%	-6%
TARRAGONA	76	65	72%	-8%
VALENCIA	76	65	72%	-8%
MARÍN Y RÍA DE PONTEVEDRA	71	65	69%	-11%
GIJÓN	67	65	66%	-13%
SEVILLA	67	65	66%	-13%
VILLAGARCÍA DE AROSA	67	65	66%	-13%

Figure 4.8, Figure 4.9,Figure 4.10graphically show the position of each port authority, ordered from highest to lowest degree of implementation and its deviation from the average when analysing the degree of total implementation, by established sectors and by merging sectors, respectively.

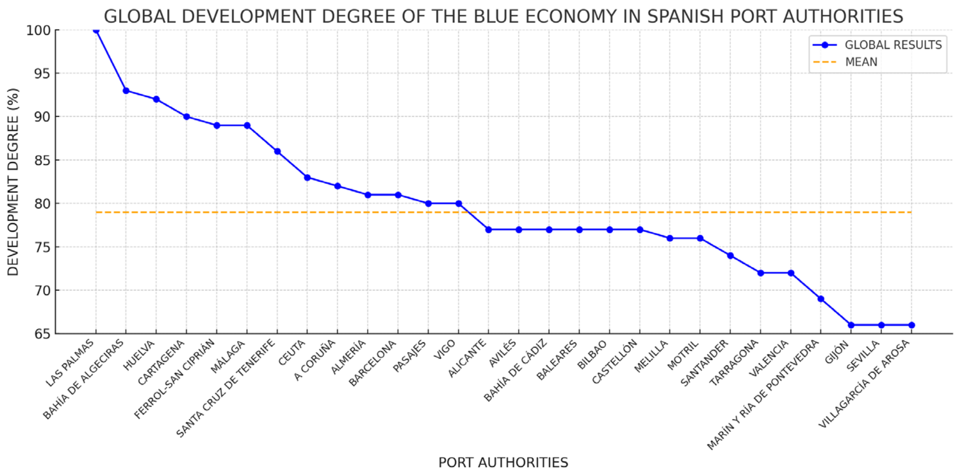


Figure 4.8: Classification of port authorities by degree of global development of the B.E. Source: own source.

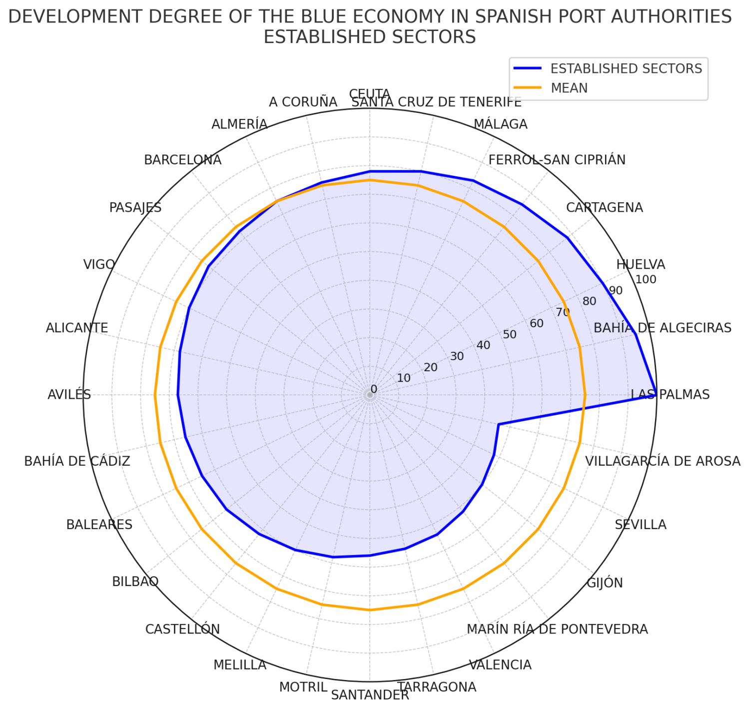


Figure 4.9: Classification of port authorities by degree of development of the established sectors. Source: own source.

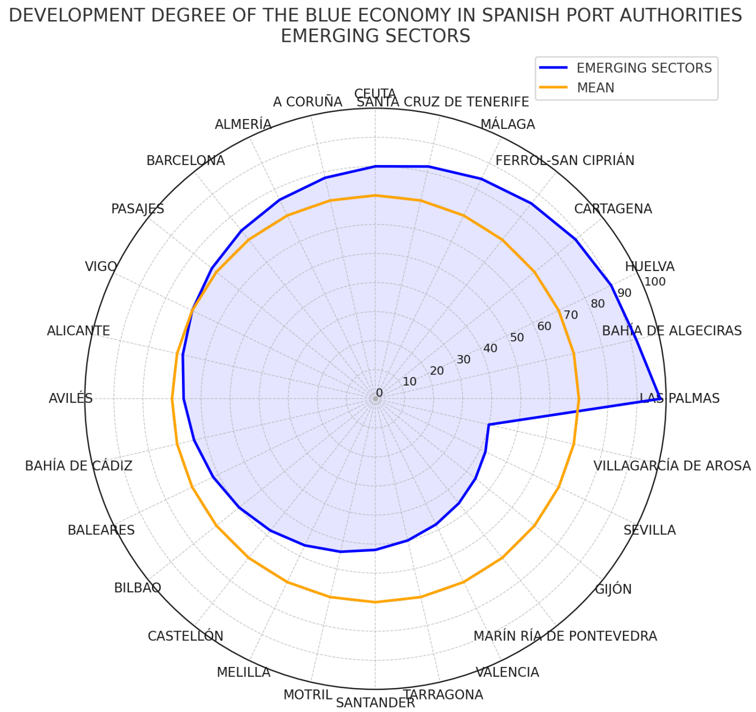


Figure 4.10: Classification of port authorities by degree of development of emerging sectors. Source: own source.

Figure 4.11and Figure 4.12 analyse the data by economic sectors instead of authorities, thus obtaining the degree of development or implementation of both the 7 established sectors and the 6 emerging ones.

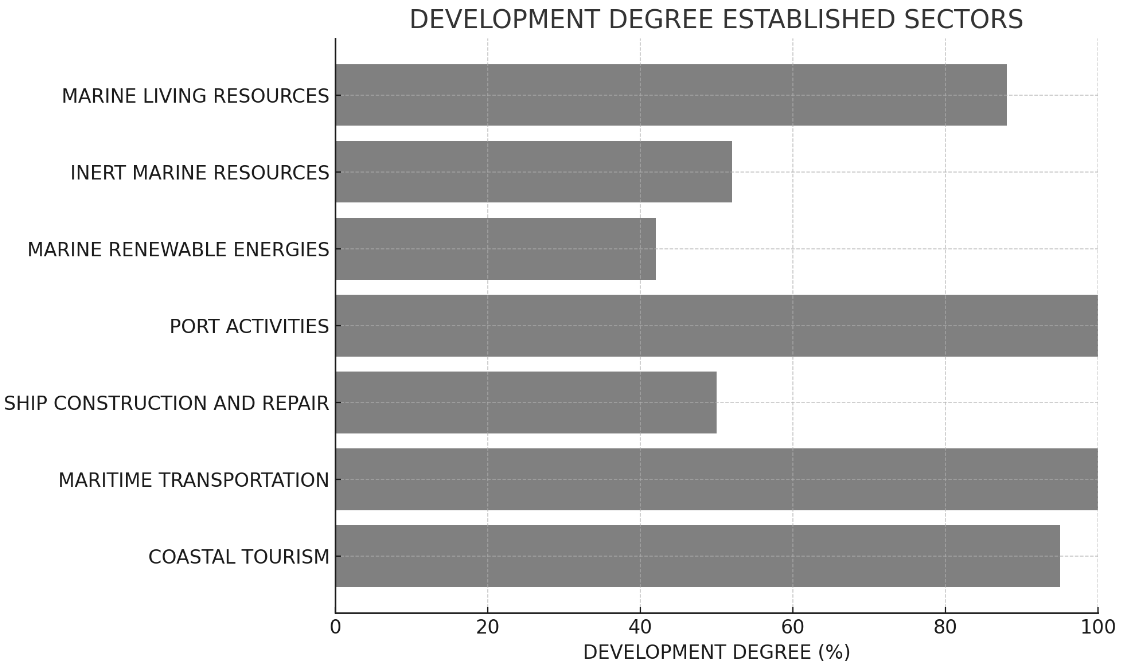


Figure 4.11:Degree of development of the sectors established in the Spanish port system as a whole. Source: own source.

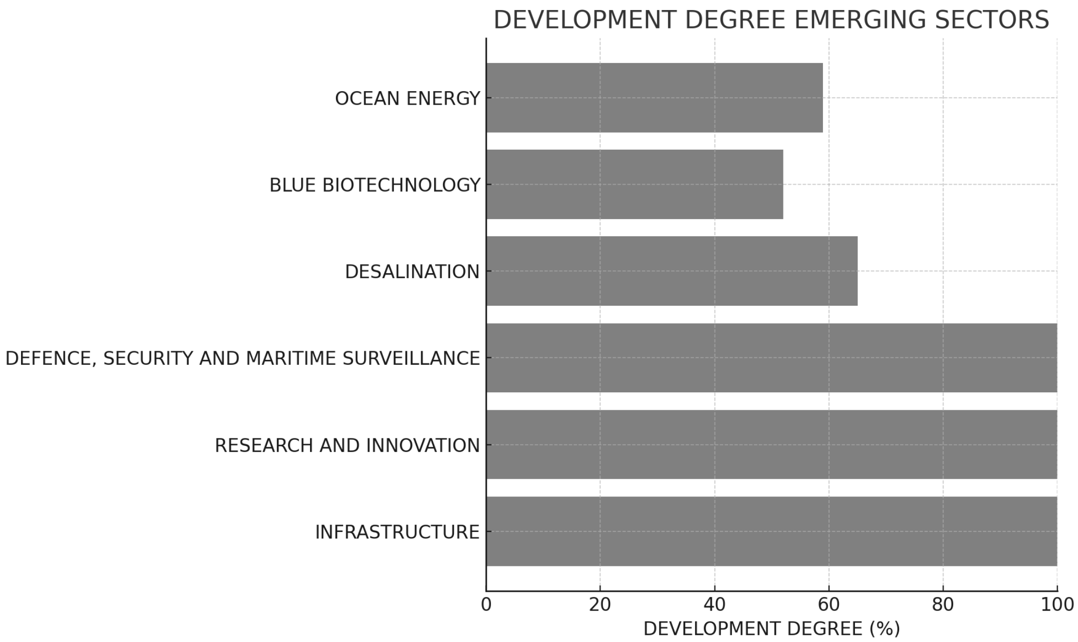


Figure 4.12: Degree of development of emerging sectors in the Spanish port system as a whole. Source: own source.

4.4. Analysis of results

An analysis of the global data on the implementation of the B.E. in Spanish ports (Table 3 and Figures 8, 9 and 10) shows that this implementation has an average of 78% throughout the system. Above this average are 13 of the 28 port authorities, with Las Palmas standing out in first place as this port develops projects related to each of the 13 sectors evaluated. This port obtains the highest score in the evaluation of both established and emerging sectors. These records are justified by the fact that Las Palmas is an island port, located in the Canary Islands. It has a strategic position in the Atlantic for north-south connections, it enjoys high strategic differentiation as it is currently developing projects in each of the dimensions evaluated, from the promotion of tourism to the development of off-shore renewable energy, through the construction and repair of ships. In addition, port authority is actively promoting high economic dynamism.

The port that lags behind the most in the implementation of this type of project is Villagarcía de Arosa, which is, on average, 13 points below the national average.

Other organisations such as Bahía de Algeciras, Huelva or Cartagena obtained results above 90%, a very relevant figure when it comes to Bahía de Algeciras as the main Spanish port by volume of traffic. These ports show excellent results despite being in different geographical areas and being of different sizes. The key of these ports is the differentiation in the development of projects, with their strategic plans they try to develop actions in most dimensions.

It is observed that for both established and emerging sectors (Figures 9 and 10) there are large differences between Port Authorities. Ports such as Villagarcía de Arosa; Gijón and Seville are more than 30 points behind Las Palma and 13 points below the national average.

A noteworthy case is that of the port of Valencia, this port is the leader of the Spanish port system in terms of container traffic, so its importance for the system is notorious, but on the other hand, when evaluating the degree of implementation of both established and emerging sectors, it ranks 24th out of 28 in both cases. This is a far cry from the national average and from the top positions that a port of such importance is supposed to occupy.

To conclude this analysis of results, it should be noted that if the degree of development of the economic sectors established in Spain as a whole is measured, coastal tourism, port activities and maritime transport clearly stand out, all of them above 95% development (Figure 11), however, the marine renewable energy sector barely exceeds 40%. Thus clearly observing a very uneven development between sectors. If the emerging sectors are analysed (Figure 12), it is obtained that practically all port authorities are developing projects related to the economic sectors of infrastructure, research and security, the sector that is in last position among the emerging sectors in terms of degree of implementation is blue biotechnology, with just over 50%.

4.5. Conclusions

First of all, the main objective of the article has been met, to create a model for evaluating the degree of implementation of the different sectors of the B.E. in Spanish ports. It is concluded that all Port Authorities actively promote the development of the B.E., since the average degree of development of all the sectors involved in the B.E. is 80% in the Spanish port system as a whole.

Undoubtedly, it can be said that the priority given to the exercise of the established dimension in comparison with the emerging dimension is justified. This preference may be due both to the greater importance of the activities involved, and to the more advanced level of technological development that it currently presents. In addition, the activities of established sectors are associated with a lower economic risk for investors (they are activities that have already been tested and developed in different places and under different conditions).

It should be noted that the ratings obtained with this model are inherently variable, as they are subject to different economic, social and political dynamics in addition to the technological development that does not stop occurring. For all these reasons, it is important to study the economic activity in each port with some regularity, since its evaluation may change.

In addition, the categorization of each dimension or economic sector into one of the two groups (established or emerging) is also subject to variation since, with the advances generated in the coming years, these activities with less development may experience exponential growth that places them above those already established, thus altering the classification established in the analysis.

On the other hand, it highlights that 13 of the 28 Spanish Port Authorities exhibit a level of overall B.E. development that exceeds the general average. This is due to the boost in the activities of established sectors that have a higher degree of development than emerging ones. For this reason, it is considered necessary to promote the emerging economic sectors as they have greater capacity for growth.

Also noteworthy is the difference of more than 30 points that exists between different port authorities, for example, the Port of Las Palmas obtains 100%, the maximum rating, but Villagarcía de Arosa 66%, 34% difference. This is a great inequality in the Spanish port system that as a proposal to reverse it, it is recommended to use this degree of development as a factor to be taken into account in the annual economic distribution of the Interport Compensation Fund, a mechanism of solidarity between the Spanish port authorities.

To conclude, this tool for comparing Port Authorities is a valuable method to analyse the barriers and potentialities of Spanish ports in the development of the B.E., providing a more comprehensive view of each port in question, allowing its strengths to be promoted and promoted, as well as addressing and improving its weaknesses. It can be a tool used to carry out comparative analyses between the entities that manage Spanish ports, or with another differentiated objective: to promote the exercise of certain activities that allow a strategy to promote the growth and development of different points of the coast, individually or through the coalition of several Port Authorities, which are known as maritime facades.

As an example, it is proposed that the potential of the strengths of the Mediterranean coast will make Spanish ports strong in the promotion of coastal tourism or desalination, while the union of the Atlantic façade can promote activities such as maritime transport or maritime renewable energy or the creation of Hubs in ports to carry out the so-called energy transition.

This study, which can focus on promoting a coalition, or to establish a differentiation between ports, could serve as a basis for future analyses in which the implications of the research developed in this work are further explored, providing a solid basis for strategic decision-making and the implementation of policies that promote the development of the B.E. in Spanish ports.

The assessment of differences of 1% or 10% in terms of the implementation of the Blue Economy in Spanish ports could be approached from various perspectives, among which cost analysis could be a key consideration. For future lines of research, firstly, the economic impact of the implementation of specific projects in each port and sector could be examined. Cost-benefit evaluations could be carried out to determine the efficiency of investments and compare returns between ports with differences of 1% or 10% in the implementation of the Blue Economy.

In addition, a detailed analysis of the financial resources allocated to each port and sector could be carried out, identifying the areas in which ports with higher levels of implementation invest compared to those with lower levels. This could reveal spending patterns and allow for strategic adjustments to optimize resource allocation.

Finally, another way to assess these differences could be by measuring the operational efficiency and productivity of projects at each port. Key performance indicators (KPIs) could be compared across ports to identify successful practices and areas for improvement.

5. DIGITAL TRANSFORMATION IN SPANISH PORT SYSTEM

This chapter presents the accepted manuscript of RA2 that has been published in a peer-reviewed and indexed book:

González-Cancelas, N., Camarero Orive, A., Vaca Cabrero, J., & Soler Flores, F. (2024). **Digital Transformation in Spanish Port System**. IntechOpen. doi: 10.5772/intechopen.1004329.

Abstract: the Spanish port system is a modern port system located on the main transport routes in the world, the digital transformation associated with the port world is being a priority element of development to enhance efficiency. Technologies such as Digital Twins, the Metaverse or the Internet of Things are key tools for the optimization of port processes, real-time collaboration, scenario simulations. It also highlights the improvement in the efficiency and safety of port operations. An affinity matrix is used to study the factors driving the transformation towards "metaports". In the context of land transport associated with ports, the importance of digitalisation is underlined and a cross-cutting approach to consolidate "smart dry ports" is suggested. The analysis concludes by highlighting challenges such as the lack of interoperability and obsolete technologies, proposing priority actions such as the renovation of infrastructures and investment in staff training to achieve an efficient and competitive Spanish port system by 2030.

Keywords: Digitalization, Port Modernization, AI in Port Operations, Sustainable Port Management, IoT in Ports.

5.1. 1. Introduction

The Spanish port system is a modern port system located on the main transport routes in the world, which is why the digital transformation that surrounds us is being a priority element of development to enhance the efficiency, competitiveness and sustainability of the system itself, transforming the way in which ports operate.

Port operational processes are being redefined with the adoption of these new technologies, as well as enabling new decision-making processes in ports.

The way ports are addressing contemporary challenges is being championed by digital transformation.

In this chapter you will explore the key developments, success stories and challenges associated with digital transformation in the Spanish port system, highlighting how these initiatives are shaping a more efficient, smarter and more sustainable future for the sector.

The digital transformation is having a significant impact on the Spanish port system, the port system is taking its first steps and needs to continue advancing so that with the use of new technological tools they are improving the efficiency, sustainability and security of ports, which is positioning them as key players in the global economy.

Throughout this chapter, the challenges faced by Spanish ports in the digital transformation process will be presented, as well as the opportunities offered by digital transformation for Spanish ports and the future trends of digital transformation in the Spanish port system.

5.2. Digtal Governance

In the contemporary era, society finds itself deeply entrenched in a technological age, wherein ports, both in Spain and globally, are increasingly becoming integral to this transformative landscape. The imperative of digital transformation is undeniable within the business sector, exerting profound influences on industries closely associated with it.

Ports, identified as pivotal nodes in transportation networks [1], witness the repercussions of this technological wave, with direct implications for seaports. In the contemporary landscape, seaports play a crucial role in facilitating the secure and efficient flow of goods across the global logistics network. Moreover, they contribute by offering diverse value-added logistics services, thereby supporting strategies such as the deferral of the global supply chain [2].

In the context of evolving global dynamics, encompassing new communication methods, changing behaviors, and the integration of innovative technologies, ports find themselves inseparable from these emerging trends. They are compelled to assume an active role in this global transformation, positioning themselves as central elements in this paradigm shift [3].

Before delving into the realm of Digital Governance, it is prudent to comprehend the concept of governance itself. Governance is defined as the art or method of administration that seeks to achieve enduring economic, social, and institutional development. It advocates for a harmonious equilibrium among the State, civil society, and the market economy. The governance process involves decision-making, priority negotiation, power utilization, and the inherent values expressed throughout the process [4].

The notion of "digital" remains ambiguous for many port organizations. It is essential to recognize it as a "long-term process, requiring continuous structural, functional, and strategic transformations" [5].

5.2.1. Strategic Framework for Spain's Ports and Digitalisation

The relationship between the strategic framework [2] of the Spanish port system and digitalisation is crucial in the current context, where global competitiveness and technological evolution are rapidly transforming the maritime industry. Spain has a state-owned port system made up of 46 ports of general interest managed by 28 Port Authorities, constituting an extensive network of ports that plays a fundamental role in international trade. In addition, Spain has a privileged geostrategic position that allows it to take advantage of the opportunities that innovation can offer to improve the efficiency, sustainability and competitiveness of its ports.

The Spanish port system has undergone significant modernisation in recent decades, driven by the growing importance of international trade and the key role of ports in the global logistics chain. In this sense, digitalisation has become a key and essential factor in maintaining and improving the competitive position of Spanish ports on the international stage.

The Strategic Framework of the Spanish port system has been drawn up by Ports and was approved by Ministerial Order of the MITMA, published in the Official State Gazette on 26 October 2022. The document focuses on the economic (activities), environmental (environment) and social (institutional) dimensions and considers efficiency, connectivity, digitalization, innovation, sustainability, security and transparency as criteria for action. These criteria are developed through sixteen strategic lines related to thirteen of the seventeen sustainable development goals agreed at the United Nations on September 25, 2015.

Digitalization is presented as a fundamental tool to achieve these goals effectively and sustainably. The monitoring and facilitation of port activity, agile and efficient inspections and administrative procedures and the development of a digital port administration, developing smart and synchronodal ports are the strategic lines that develop the criterion of action related to digitalisation.

In the last decade, digitalisation has emerged as a catalyst and transformer in the port sector, highlighting the importance of digitalisation in the Spanish port system in terms of operational efficiency, competitiveness, sustainability, effective management and safety.

Improved operational efficiency: Digitalisation in the Spanish port system has introduced innovations that optimise the different port operations. Digital port management platforms enable real-time monitoring of port activities, facilitating data-driven decision-making. In addition, digitalized planning and coordination systems contribute to the reduction of waiting times, the improvement in the allocation of resources and the minimization of logistical bottlenecks. The implementation of technologies such as the Internet of Things (IoT) has enabled greater visibility and traceability of cargo throughout the supply chain, improving synchronization between the actors involved, from shipping companies to logistics companies and port authorities.

Increased international competitiveness: Digitalisation has established itself as a fundamental differentiating factor for ports seeking to attract and consolidate port traffic. The ability to offer efficient, transparent and technologically advanced services is essential to position itself as an internationally competitive port. In this sense, the automation of processes, the implementation of autonomous vehicles for cargo handling and the adoption of robotic technologies contribute to greater efficiency and productivity, key elements to stand out on the world stage.

Contribution to environmental sustainability: Digitalisation has made it possible to implement more sustainable practices in the Spanish port system, through route optimisation, smart energy management and emissions reduction are areas in which technology has proven to be a valuable ally. In addition, digitalization allows better monitoring of the environmental impact of port operations, facilitating the adoption of corrective measures and compliance with increasingly stringent environmental regulations.

Development of effective management: The adoption of technological innovations is essential for effective port management. Digitalization not only involves the implementation of advanced technologies, but also the incorporation of artificial intelligence (AI) systems and data analytics for predictive decision-making. The ability to foresee potential problems, optimize operations, and adapt quickly to changes in demand is crucial in a dynamic port environment.

Strengthening security: Digitalization plays a critical role in improving port security. Implementing advanced cybersecurity systems protects critical data and port operations from potential threats. In addition, the use of technologies such as smart surveillance cameras and facial recognition systems contributes to strengthening physical security in the port environment.

All in all, digitalisation is currently considered an essential component for the development and continuous improvement of the Spanish state-owned port system. Investment in digital technologies and the adoption of innovative practices are imperative to ensure that the Spanish port system is perfectly adapted to today's challenges and is prepared to lead the future of logistics and maritime trade.

5.3. Digital Simulation in Ports: Digital Twins and Metaverse

5.3.1. Introduction to digital transformation in Spanish ports

The developed world of the twenty-first century is constantly changing and evolving. This is a consequence of digital evolution. The port sector is betting on this change. The transversal digital transformation of all its services triggers an improvement in resource dedication, process optimization, reduction of operational risks of failure, etc. [69]. This generates a new way of working to which the sector itself has to adapt, such as new jobs, training for the organization, acquisition of new equipment [70].

In the context of Spain, Port Authorities are tasked with defining a strategic roadmap for the digital implementation and adaptation of port facilities. This commitment is evident in numerous initiatives that gain prominence year after year. The tangible shift toward digitalization is not merely a transient trend; it has solidified as a lasting reality. The Spanish government is resolutely dedicated to fostering development through digitalization, with a specific focus on realizing Smart Cities, Industry 4.0, and the concept of a Smart Port [71].

A cornerstone in this pursuit is the 'Ports 4.0' capital fund, serving as the corporate open innovation model adopted by Puertos del Estado and Spanish Port Authorities. This model aims to attract, support, and facilitate the application of talent and entrepreneurial initiatives within the Spanish logistics-port sector, both in the public and private domains, against the backdrop of the ongoing Fourth Industrial Revolution [25].

The primary objective of Ports 4.0 is to actively promote and integrate disruptive or incremental innovations as key components enhancing competitiveness, efficiency, sustainability, safety, and security within the Spanish logistics-port sector. This applies to entities in both the public and private realms, facilitating their transition towards the utilization economy of the 4.0 era [23].

5.3.2. Digital Twins in the port operation

Digital twins are a virtual representation of objects or systems throughout their lifecycle designed to accurately reflect and provide vital information about the different areas of functionality of the object or system [72].

They expose information on different aspects at a physical level, such as performance, technical characteristics, repair history, services, etc. This data provides us with the information to carry out simulations, analysis of improvements, creation or increase of business value, and above all to have technical support for decision-making [73].

Digital twins are used in many different types of industries with different goals. They are used to carry out simulations to test hypotheses and observe how these models respond, to know the result that a decision on real assets will have: consequences, risks involved, downtime involved, etc.[74].

Digitalization has drastically changed the way businesses and industries operate, and ports are no exception. The digitalization of ports involves the adoption of digital technologies to optimize the management of port operations, improve efficiency and reduce costs.

One of the most exciting developments in the digitalization of ports is the creation of digital twins. A digital twin is an accurate and detailed digital representation of a physical object or system in real time. In the case of ports, a digital twin is a virtual replica of port operations, using real-time data to simulate and optimize port processes.

Digital twins are created using technologies such as the Internet of Things (IoT), artificial intelligence (AI), and augmented reality (AR). For example, sensors installed in the port can collect real-time data on traffic flow, workload, and the status of port equipment and infrastructure. This data is used to create a virtual replica of the port that can be used to analyze and improve the performance of port operations.

Digital twins can provide a complete and accurate view of port operations, enabling port managers to make more informed decisions and optimize port processes. In addition, digital twins can be used to simulate different scenarios and make accurate predictions about the impact of changes on port operations.

Digital twins in ports are revolutionizing port management by providing real-time insight and more accurate assessment of port activity. This allows port authorities and maritime companies to improve efficiency and safety in the management of their operations and increase their competitiveness in the maritime sector [42].

Digital twins in ports and the maritime sector use a combination of data analytics technologies to collect, process and analyse data in real-time and improve management and efficiency in the maritime sector [43].

In Spain, some ports that are using "digital twins" include:

- Port of Barcelona: The Port of Barcelona is using "digital twins" to improve cargo management and logistics and to monitor activity at the port.
- Port of Algeciras: The Port of Algeciras is using "digital twins" to improve efficiency in cargo management and logistics and to monitor activity at the port.
- Port of Valencia: The Port of Valencia is using "digital twins" to monitor and optimize cargo management and logistics and to improve efficiency at the port.

These are just a few examples of Spanish ports that are using "digital twins". With the rise of technology and the adoption of "digital twins" around the world, it is likely that we will see an increase in the use of "digital twins" in Spanish ports in the future [75].

The relationship between the different factors that will drive digital twins in the Spanish port system can be determined through the use of an affinity matrix.

An affinity matrix is a planning tool used to organize and classify large amounts of information or ideas into related topic groups. It is also known as a KJ diagram, K-J matrix, correlation matrix, K-J diagram, or K-J method.

The affinity matrix is commonly used in problem-solving and group decision-making processes. Instead of just brainstorming and letting ideas flow in a disorganized way, the affinity matrix helps participants organize and categorize related ideas.

It is possible to group the factors in the affinity matrix based on their relationship or similarity. The grouping proposed by the panel of experts is (Figure 5.1):

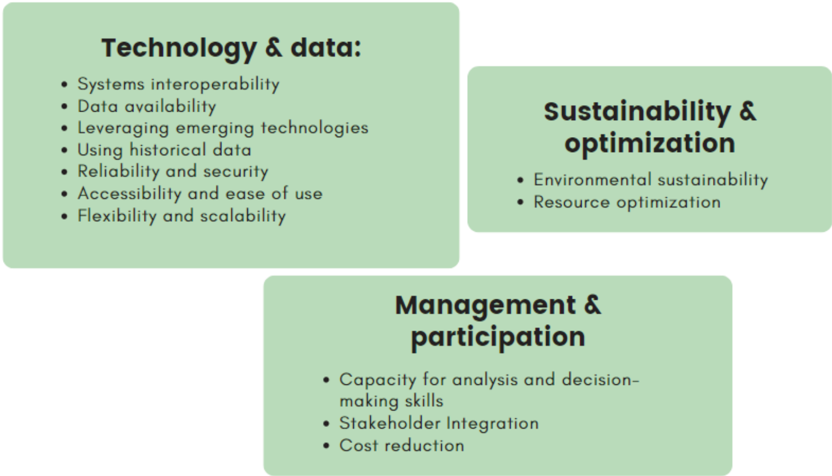


Figure 5.1: Affinity matrix. Source: own source.

This matrix represented in Table 5.1 can help identify the factors that may influence the success or failure of the implementation of Digital Twins in ports. Positive factors can help you define the benefits you can reap from Digital Twins, while negative factors allow you to identify challenges you need to face. Neutral factors may not have a direct impact on the implementation of Digital Twins in ports, but it is important to take them into account when making decisions.

Table 5.1: Factors classification for implementation of Digital Twins in ports. Source: own source.

Positive factors	Neutral factors	Negative factors
Improved efficiency and productivity	Lack of knowledge or training in the technology	Implementation Costs
Increased safety and risk reduction	Need for a significant upfront investment	Resistance to change
Improved decision-making	Data Availability	Interoperability with existing systems
Increased planning and design capabilities	Limited scalability	Cybersecurity Risks
Improved asset and resource management	Environmental and social impact	Reliance on external suppliers
Increased customer satisfaction and improved user experience	Infrastructure and connectivity requirements	Potential conflicts with dock workers

Digital twins offer a great opportunity to improve efficiency and productivity in Spanish ports. By creating a virtual replica of port processes and infrastructure, digital twins enable better management and monitoring of resources, as well as more informed decision-making.

Some of the advantages of digital twins in Spanish ports include better capacity planning and resource management, reduced downtime, and increased security in port operations. In addition, digital twins also allow for better coordination between the different actors in the logistics chain and the optimization of cargo logistics.

However, the implementation of digital twins also presents some challenges, such as the need for accurate and up-to-date data, investment in technology, and training staff in managing digital twins. In addition, it is important to take into account the privacy and security aspects in the management of the data used in digital twins.

Digital twins offer great potential to improve efficiency and productivity in Spanish ports, although their implementation requires careful planning and investment in technology and staff training. If properly addressed, digital twins can be a valuable tool to improve the competitiveness of Spanish ports in the global market.

5.3.3. Metaverse: An Innovative Perspective in Ports

The concept of the metaverse encompasses a shared virtual universe, computer-simulated to enable real-time interaction and experiences for users. This immersive experience is made possible through virtual, augmented, or mixed reality, featuring 3D representations of individuals, objects, and environments. The overarching objective of the metaverse is to construct a virtual realm where users can engage and encounter an alternative reality distinct from their everyday lives.

Considerable progress has been made in the metaverse across various domains, including video games, entertainment, education and training, business and commerce, and virtual reality. Notably, the video games and entertainment sector has witnessed significant strides in recent years, propelled by the surge in online gaming popularity and the escalating demand for immersive experiences. While substantial advancements have occurred in video games and entertainment, ongoing exploration is unfolding in diverse sectors like education and training. Here, metaverse solutions are being actively developed to enhance the effectiveness and efficiency of teaching methodologies. Anticipating the future, further strides in the metaverse are likely across a broad spectrum of industries.

Overall, the metaverse has many advantages, such as real-time interaction, immersive experience, and accessibility, but it also has some drawbacks, such as technical requirements, cost, and cultural barriers. It's important to carefully evaluate these factors before embracing the metaverse.

The metaverse is starting to be used in maritime traffic as a way to improve efficiency and collaboration in the supply chain. Some examples of how the metaverse is being used in maritime traffic include:

Maritime traffic imulation: The metaverse can be used to simulate maritime traffic and assess how different scenarios may affect efficiency and safety.

Route planning: The metaverse can be used to plan routes and assess navigation efficiency in real-time.

Real-time collaboration: The metaverse can be used to enable supply chain teams to collaborate in real-time in a virtual environment, which can improve efficiency and communication.

Training and coaching: The metaverse can be used to train and coach maritime workers in a safe and controlled environment.

Overall, the metaverse is starting to be used in maritime traffic as a way to improve efficiency and collaboration in the supply chain. We are likely to see more adoption of metaverse technology in the future in this sector.

Determining the most advanced Spanish port in the metaverse presents a challenge due to the novelty of this concept and the ongoing research and development efforts across various ports. Additionally, assessing the "advanced" status of a port can be subjective, contingent on diverse criteria like investment quantity and the quality of implemented technology. Consequently, unequivocally pinpointing the most advanced Spanish port in the metaverse is not feasible.

Nevertheless, it is plausible that certain ports are actively engaging in research and experimentation with metaverse technology to enhance efficiency and user experiences. For instance, ports might be exploring the application of the metaverse to offer virtual travel experiences to passengers before their physical arrival or to establish a platform for real-time collaboration and decision-making with supply chain partners.

In the near term, the metaverse is anticipated to undergo further evolution and increased popularity, finding applications in diverse fields such as entertainment, gaming, education, commerce, and virtual reality. Furthermore, there is an expectation that the metaverse will exert a substantial impact on the economy, ushering in new business opportunities and job creation linked to virtual reality technology.

The strategy of Spanish ports to become ports in the metaverse or metaports can be studied using an affinity matrix.

In the Figure 5.2 it can be seen the affinity matrix.

With the second panel of experts, the following elements were obtained (Table 5.2):

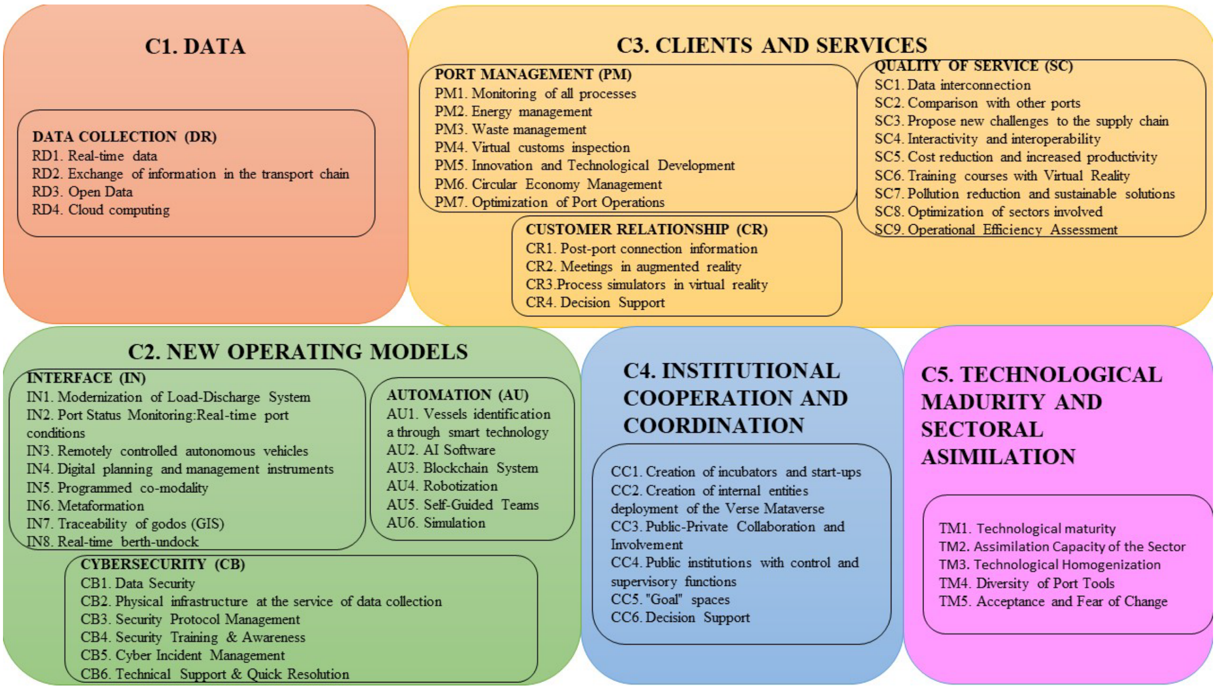


Figure 5.2: Affinity matrix. Source: own source.

Table 5.2: Weights in the Affinity Diagram. Source: own source.

CATEGORY	CATEGORY WEIGHT	SUBCATEGORY	SUBCATEGOY WEIGHT	KEY ELEMENT
C1- DATA	30%	DR-DATA COLLECTION	100%	RD3- Open data
C2- NEW OPERATING MODELS	10%	IN- INTERFACE	30%	IN4- Digital planning and management instrument
		AU- AUTOMATION	20%	AU2- AI software
		CB- CYBERSECURITY	50%	CB1- Daa security
C3- CLIENTS AND SERVICES	15%	PM- PORT MANAGEMENT	60%	PM7- Decision support
		SC- QUALITY OF SERVICE	25%	SC9- Operational efficiency assessment
		CR- CUSTOMER RELATIONSHIP	15%	CR4-Decision support
C4- INSTITUTIONAL COOPERATION AND COORDINATION	10%			CC3- PPP and involvement
C5- TECHNOLOGICAL MADURITY AND SECTORAL ASIMILATION	35%			TM1- Technological madurity
				TM2- Assimilation capacity of the sector

The categories with the most extensive array of indicators pertain to novel operating models and customer-centric services, and it is within these categories that substantial efforts will be required.

Under the umbrella of operating models lies automation, and the metaverse holds the potential to facilitate the deployment of autonomous systems for the transportation, loading of goods, and maintenance and repair of port equipment. These systems could be remotely managed and observed in real-time through the metaverse, thereby reducing the dependence on human involvement and mitigating risks associated with workplace accidents.

In terms of cybersecurity, ensuring security is paramount in port operations. Within the metaverse, it becomes feasible to simulate risk scenarios and test security measures to evaluate their efficacy before implementation in the real world. Moreover, the metaverse could serve as a platform for continuous monitoring and immediate detection of potential security threats, enabling a prompt and effective response to emergency situations.

Based on the identification of driving elements for the transformation of Spanish ports into "metaports" by the panel of experts, several key conclusions can be drawn:

- Technology and Digital Transformation: Technology and digital transformation are fundamental elements for the modernisation of Spanish ports. The adoption of advanced technologies, such as virtual reality, artificial intelligence, and automation, plays a crucial role in improving operational efficiency, safety, and sustainability.
- Interoperability and Standards: The existence of standards and protocols in the sector is essential to ensure interoperability and system integration. This facilitates collaboration between different actors in the port and allows for the transfer of data and knowledge more effectively.
- Education and Training: Training port staff in metaverse technologies is essential for the successful assimilation of these technologies. Adaptability and the ability to learn how to use these technologies are critical.
- Cross-Sector Collaboration: Collaboration with other industries, such as aeronautics, can provide knowledge and expertise in adopting digital technologies. Collaboration and information sharing are key factors for success in port modernization.
- Promotion Policies: The existence of policies and programs to promote the adoption of the metaverse in the sector is essential. These programs may include incentives and financial support for technological modernization.

- Efficiency, Competitiveness and Sustainability: The modernization of ports not only seeks to improve efficiency and competitiveness, but also sustainability. Cost reduction, process optimization, and resource management are key elements in this transformation.
- The transformation of Spanish ports into "metaports" involves significant investment in technology and training, as well as close collaboration between actors in the port sector and other related industries. Technological modernisation and the adoption of sustainable practices are key elements for the future of Spanish ports and their ability to compete internationally in an increasingly digital environment.

5.4. Digitalization of the port with its hinterland. Ground Transportation & Smart Dry Ports

5.4.1. Digitalization of land transport associated with ports

The role of ports has evolved significantly. They are now integral components of global logistics networks, orchestrating cargo flows and providing value-added logistics services in a streamlined and effective manner. To fully embrace the digital transformation, ports must integrate their landside operations seamlessly with their core operations.

An affinity diagram is a valuable tool for organizing data, ideas, or recommendations arising from an event, such as the digitalization of land transport associated with Spanish ports. It helps to focus discussions among the working group members to identify potential solutions (Figure 5.3) [18]. Once categorized, these ideas are further scrutinized to assess their alignment with the core problem or situation. This process should lead to a series of conclusions that, in turn, guide the group towards consensus-based decisions.

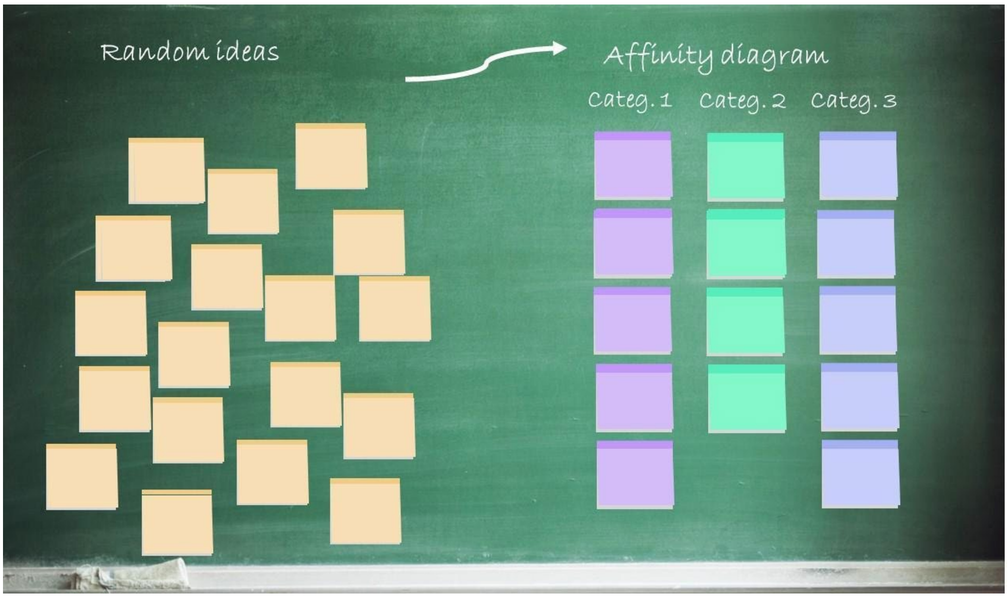


Figure 5.3: How the Affinity Diagram works. Source: own source.

Once the process of consultation and discussion of the experts is completed, the following affinity diagram is obtained (Figure 5.4).

The final grouping with respect to the digitalization of land transport associated with ports is made up of 5 different groups: exchange of goods, tracking of goods, information processing, automation and operation of the port.

Currently, Spanish ports are in a relatively high position in terms of their level of digitalization, but they continue to strive to update and innovate with the aim of improving their competitiveness in the market. One of the main remaining challenges is to achieve an immediate transition to digital, smart and sustainable ports, which can optimize existing infrastructures and increase their capacity through intelligent space management. To achieve this, the integration of technologies such as the cloud, big data and sensorization is essential. This approach will also impact the digitalization related to land transport that connects to the port.

Working in collaboration with the port community, ports must promote the creation of more efficient logistics platforms, promoting coordination and communication between the different actors in the logistics-port field. Importantly, the mere presence of these technologies does not automatically guarantee that a community will be considered "smarter" or that it will have a positive impact on the land transportation associated with the port.

In the case of Spain, five fundamental pillars are identified in relation to land transport. Although technology plays a crucial role, the determining factor in success stories is smart governance, which influences the positive development of these five identified pillars [47].

Smart governance emerges as a critical enabler for port digitalization to transcend port boundaries and seamlessly integrate with terrestrial connections. To achieve this, it is crucial to: empower all stakeholders to actively participate in decision-making within a digitally revolutionized and hyperconnected administration; leverage open data platforms to democratize information and data accessibility within the community; harness the potential of emerging technologies for smart energy management, environmental protection, and waste disposal; nurture an entrepreneurial ecosystem through collaboration with universities and research centers; and foster a culture of innovation and continuous improvement.

The transformative power of smart port governance lies in its ability to connect to a broader network of equally digitized hubs, forming a seamlessly integrated ecosystem of smart ports. This interconnected network facilitates real-time data exchange and collaboration, optimizing operations and enhancing the overall efficiency of the logistics chain. However, this digital integration must extend beyond port operations to encompass terrestrial connections, ensuring seamless and efficient cargo movement throughout the entire supply chain.

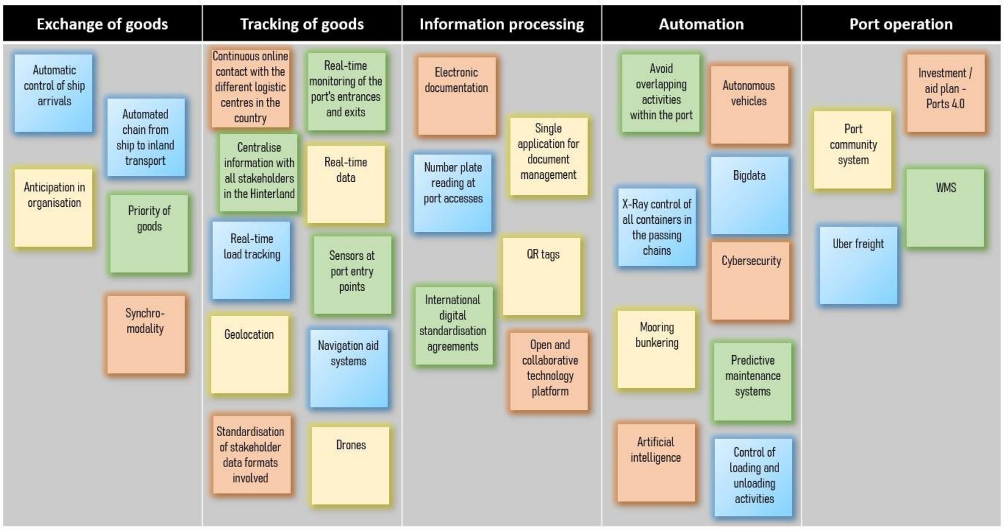


Figure 5.4: Affinity diagram groups and subgroups. Source: own source.

5.4.2. Smart Dry Ports

Extending the logistics chain from seaports to landside operations involves strategic hubs known as dry ports. The evolution of dry ports is deeply intertwined with the development of seaports, as they serve as "intermodal freight terminals located inland, directly connected to ports, the origin and destination of their cargoes, through a railway network" [20]. Just as goods seamlessly transit from maritime terminals to dry ports, so too must data and digitalization processes flow seamlessly between these entities.

The Spanish port system currently stands at the 5th generation, where the concept of Smart Ports is firmly taking root. This transformation ushers in a new era where ports function as digital logistics platforms with IoT capabilities, enabling real-time data collaboration and sharing [21]. This generation of ports hinges on the collaborative data exchange among a diverse spectrum of public and private stakeholders, extending far beyond the traditional community of operators or freight forwarders. Additionally, these smart ports integrate seamlessly with intelligent transport systems such as railways, roads, and waterways, fostering a cohesive and efficient logistics network within the broader territory. In essence, this model of digital port governance promotes effective management of both direct and indirect operations, encompassing not only the port system itself but also its extended reach.

It is considered convenient to consider the following 4 fundamental axes for dry ports: Economic, Operational, Social, Political, Institutional and Environmental (Figure 5.5).

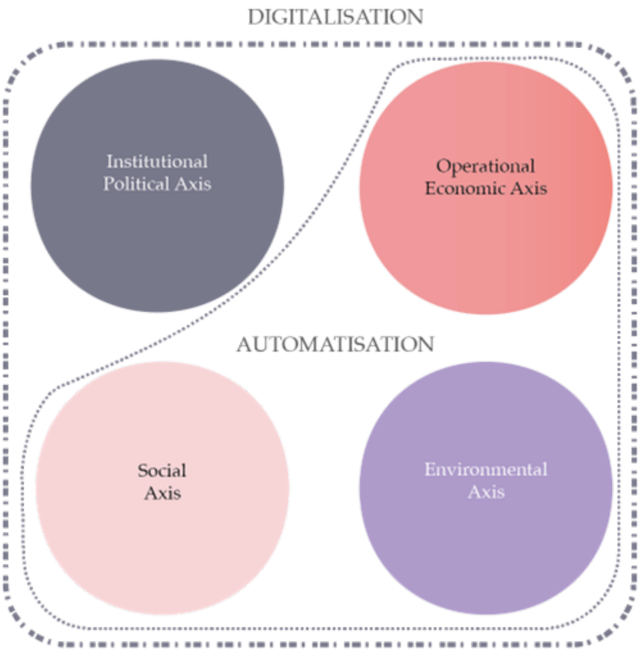


Figure 5.5: Axes of digitalization. Source: own source.

Next, the indicators that have been selected and validated by the expert system that has been consulted using the Delphi survey method are identified (Table 5.3).

Table 5.3: Weight of Axes and Indicators Proposed for the Study

AXES	ID	INDICATOR	WEIGHTS
OPERATIONAL ECONOMICS	E-1	Adaptation of infrastructures to reading integrated sensors	2,08
OPERATIONAL ECONOMICS	E-2	Transport Control for loading and unloading	2,08
OPERATIONAL ECONOMICS	E-3	Loading and unloading line efficiency	2,04
OPERATIONAL ECONOMICS	E-4	Platform Productivity	1,98
OPERATIONAL ECONOMICS	E-5	TREBES Expedition Capacity	1,92
OPERATIONAL ECONOMICS	E-6	Storage capacity	1,82
OPERATIONAL ECONOMICS	E-7	Integrated digital goods management	2,1
OPERATIONAL ECONOMICS	E-8	Internal Roads	1,86
OPERATIONAL ECONOMICS	E-9	Reception capacity Rail	1,94
OPERATIONAL ECONOMICS	E-10	Operating Area	1,97
OPERATIONAL ECONOMICS	E-11	Terrestrial connectivity	1,98
OPERATIONAL ECONOMICS	E-12	Air connectivity	1,43
OPERATIONAL ECONOMICS	E-13	Degree in Automation of mechanical systems	2
OPERATIONAL ECONOMICS	E-14	Degree of intermodality	1,89
OPERATIONAL ECONOMICS	E-15	Size of operations	1,81
SOCIAL	S-1	Worker safety	3,8
SOCIAL	S-2	Digitalization of access security	3,99
SOCIAL	S-3	Training of workers	3,53
SOCIAL	S-4	Labor inclusion and equality in the workforce	3,07
SOCIAL	S-5	Accessibility to disabled user facilities	3,38
SOCIAL	S-6	Digital interaction with the customer	3,99
INSTITUTIONAL	I-1	Transparency in management	4,59

INSTITUTIONAL	I-2	Excess of port authorities in the territory	3,52
INSTITUTIONAL	I-3	Management systems implemented	4,17
INSTITUTIONAL	I-4	Participation of public and private entities	3,83
INSTITUTIONAL	I-5	Promoting efficiency in private operators	4,14
INSTITUTIONAL	I-6	Digitalization of customs processes	4,95
ENVIRONMENTAL	M-1	Frequency of accidental spills	2,89
ENVIRONMENTAL	M-2	Environmental management systems	2,72
ENVIRONMENTAL	M-3	Actions to revalue the natural environment	2,9
ENVIRONMENTAL	M-4	Automating air quality assessment	2,6
ENVIRONMENTAL	M-5	Noise pollution	2,51
ENVIRONMENTAL	M-6	Renewable energy production	2,4
ENVIRONMENTAL	M-7	Management of electricity consumption	2,69
ENVIRONMENTAL	M-8	Use of fuels	2,8
ENVIRONMENTAL	M-9	Water consumption management	2,63

It can be seen that the indicators that have the greatest relationship with the digitalization and automation of processes and their management, obtain greater weight.

As an initial takeaway from this study, the Smart concept, which embraces the application of information and communication technologies (ICTs), must be systematically and holistically considered across the four pillars that underpin the SDP concept. Sustainability encompasses three pillars: economic, social, and environmental. Therefore, the implementation of railway and intermodal management digitalization in port facilities must be pervasive and transformative. Only through this approach can the notion of the smart dry port be firmly established, and accountability in terms of sustainability and efficiency can be achieved, ultimately leading to a positive cost-benefit outcome.

Focus should be placed on achieving a higher degree of adaptation in the environmental dimension, particularly through the acquisition of new digitalization systems and the implementation of automation in those processes that can enable greater alignment with the Smart Port concept. Enhancing this dimension does not entail significant disbursements or investments compared to the other three, which would require greater commitment and should be championed by the relevant administrations.

In conclusion, the dry ports under examination must prioritize and invest in a heightened level of digitalization and process automation, not only to enhance their efficiency and sustainability but also to augment their societal value proposition.

Digitalization is no longer an option for these types of facilities but rather a prerequisite for survival in the global logistics landscape.

5.5. Conclusions

After exploring the digital transformation in the Spanish port system, several significant conclusions can be drawn.

First, the adoption of digital technologies has boosted operational efficiency, reducing waiting times, improving logistics management, and strengthening the global competitiveness of ports.

In addition, the integration of the Internet of Things (IoT) and artificial intelligence has enabled more informed and proactive decision-making, optimizing planning and response to unforeseen events.

However, there are also challenges, such as the need to address cybersecurity issues and staff training to maximize the benefits of digitalization. With regard to human resources, the importance of having qualified and trained personnel in the port system has been observed. A lack of qualified personnel can limit the ability to adapt and respond to present and future challenges.

Currently, there is a lack of interoperability and integration in Spanish ports, which limits the efficiency and fluidity of the exchange of information. In addition, the presence of obsolete technologies and difficulties in data processing prevent the transmission of information in real time, which limits decision-making and process improvement.

Ultimately, the digital transformation has laid the foundations for a more agile, connected and sustainable Spanish port system, strategically positioning it to face future challenges and take advantage of emerging opportunities in the changing global landscape, however insufficient data storage capacity hinders the availability of up-to-date information. In addition, the absence of automation in certain processes has been identified, which affects the efficiency and productivity of the system.

With regard to human resources, the importance of having qualified and trained personnel in the port system has been observed. A lack of qualified personnel can limit the ability to adapt and respond to present and future challenges. In terms of regulations, the presence of restrictive regulations and constant changes in policies has been identified.

Based on this analysis, it is concluded that the Spanish port system needs to evolve in order to overcome these challenges and improve its operation. It is essential to promote interoperability and integration between the different components of the system, as well as to adopt more advanced technologies that allow for the smooth processing and transmission of data in real time.

A renewal of infrastructures is required to allow for greater connectivity, greater data storage capacity and greater automation in processes. Therefore, it is essential to invest in the training and development of staff, ensuring a qualified and skilled team that can face current and future challenges. In addition, it is recommended to establish a more favorable regulatory environment, with clear and stable regulations that promote the agility and adaptability of the port system. These actions will allow greater efficiency, competitiveness and sustainability in the port system, improving the quality of services and strengthening its position in the international arena.

These key areas represent the most significant obstacles to achieving optimal fluidity in data exchange and effective digitalization of the port system. Addressing these issues as a priority will lay a solid foundation for driving digital transformation and improving operational efficiency.

It is essential to allocate adequate resources, both financial and human, to these priority actions. This involves collaboration and coordination between stakeholders, including Port Authorities, State Ports and the different bodies involved. In addition, it is important to foster a favourable environment for innovation and the development of advanced technological solutions that enable the transformation towards smart and sustainable ports.

To meet the digitalisation objectives, set out in the strategic framework for 2030 in the Spanish port system, actions that require immediate action must be prioritised. Addressing the challenges identified in critical areas, as well as fostering medium and long-term improvements in other categories, will allow us to move towards a modern, efficient port system prepared to face the challenges of the future. This will boost competitiveness, sustainability and quality in the Spanish port system, positioning it as an international benchmark.

6. ANALYSIS OF THE DIGITAL GOVERNANCE OF PORTS

This chapter presents the accepted manuscript of RA2 that has been published in a peer-reviewed and indexed journal:

González-Cancelas, N., Camarero Orive, A., Vilarchao, A. R., & Vaca-Cabrero, J. (2024). **Use of End-to-End Tool for the Analysis of the Digital Governance of Ports**. *Logistics*, *8*(2), 58. https://doi.org/10.3390/logistics8020058

Abstract: *Background:* There is currently a challenge of digital governance in the context of ports, where efficiency and transparency are key elements for the success of operations. In ports, the effective adoption of digital governance can have a significant impact on optimizing operational processes and improving coordination between port authorities, logistics operators and customs. *Method:* in this context, the article proposes the use of End To End Tool to analyze and evaluate digital governance in ports. This tool makes it possible to collect data from various sources, carry out a thorough analysis of the processes involved and evaluate the satisfaction of end users. In addition, it provides an intuitive and easy-to-use interface to visualize results and make evidence-based decisions. The outcomes revealed areas of improvement in operational processes, identified bottlenecks and presented proposals to optimize port efficiency. *Results*: the port currently exhibiting the best digital governance is Valencia, followed by Piraeus, Barcelona, and Algeciras, with very comparable management, and finally, Genoa. *Conclusions:* efficient public-private collaboration in digital governance boosts port competitiveness. Regulatory frameworks for data security are crucial, the digital governance evolves as vital for global success.

Keywords: data management; digital governance; ports; digitalization; end to end tool.

6.1. Introduction

In the last decade, the rapid evolution of information and communication technologies has fundamentally reshaped global port management. The emergence of digital governance within ports stands out as a pivotal strategy aimed at enhancing operational efficiency, safety, and sustainability within these critical logistical frameworks [40].

Today, ports play a very important role in the industry, allowing the economic development of the countries in which they are located. Globally, ports engage in continual competition to provide superior services and ensure seamless cargo movement while also prioritizing environmental sustainability through the modernization of their processes and technologies [76].

In Spain's case, its peripheral location within Europe, coupled with its extensive coastline spanning approximately 8,000 kilometers—the most among European countries—positions Spanish ports as pivotal drivers of economic growth and advancement. They not only serve as key hubs for logistics but also act as catalysts for regional prosperity, contributing significantly to the economic progress of the southern European continent [77].

Due to the importance of ports as a business hubs, digitalization is a crucial aspect to take into account [78]. The digital transition, automation of practices and processes and the implementation of other cutting-edge technologies, are gaining strength in the global maritime-port field and methods are being sought to end the tedious and complicated traditional procedures that are done on paper, to give way to intelligent solutions based on the cloud, Big Data, Artificial Intelligence and the Internet of Things (IoT) [79].

Nevertheless, this industry lags behind others in terms of digitalization due to the formidable challenge of achieving consensus and collaboration among all stakeholders within the transport chain. Additionally, notable discrepancies exist in the pace of digital transformation across different countries [40].

Therefore, the original function of ports to connect sea and land has evolved into global logistics centers that manage the flow of goods and provide value-added logistics services in an efficient and environmentally friendly way [40].

These modern ports are based on three fundamental pillars (Figure 6.1), infrastructure, a classic element of Civil Engineering; the services offered by the port to the different participating agents and the infostructure or data management [18]. This final pillar underscores the essence of digital governance, which entails the utilization, processing, and management of data gathered through tools that have emerged with digital advancement to effectively administer a port. In essence, digital governance in the port administrative domain revolves around harnessing technological innovations to streamline operations and decision-making processes [18].

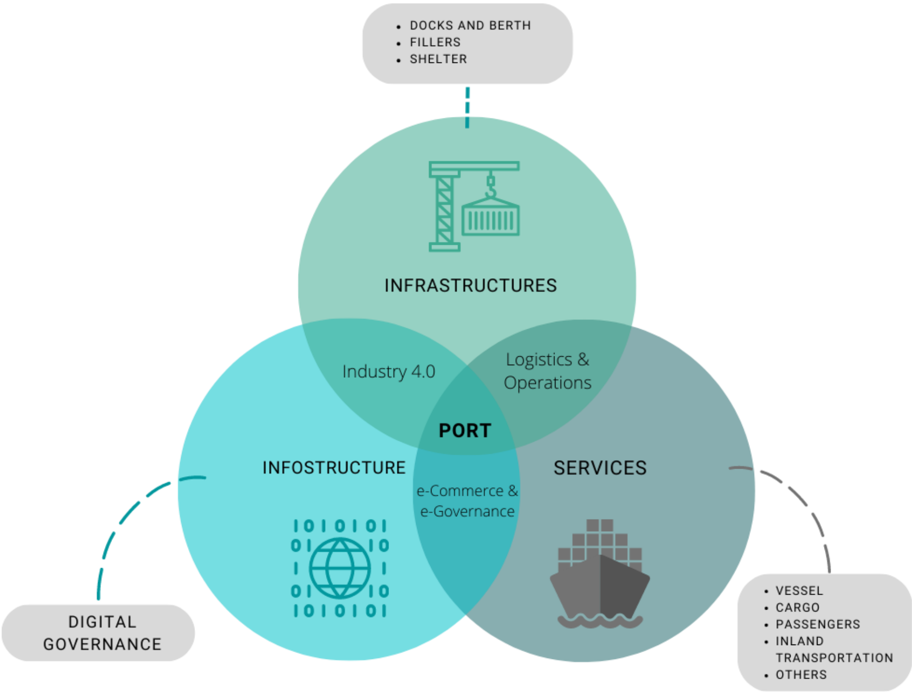


Figure 6.1: Fundamental pillars of a modern port. Source: own elaboration.

It is essential to recognize the current challenges in the digital governance of ports. The complexity of port operations, coupled with the need for coordination between multiple actors, poses significant challenges in terms of efficiency and transparency. The research, using the End to End tool, seeks to address these challenges by analysing detailed digital governance in Mediterranean ports and identifying areas for improvement. By providing a comprehensive, evidence-based assessment, contributions have the potential to inform and improve existing practices in this field, thereby contributing to the advancement of port management.

The rest of this article is organized as follows: Section 2 presents the state of the art of current port digital governance, highlighting the crucial collaboration between public and private sectors, which offers benefits such as operational optimization. The future entails automation and coordination between modes of transportation, requiring continuous evaluation and adaptation, as demonstrated by a detailed description of the proposed method using the End-to-End tool. Section 3 explains the End-to-End Tool methodology, followed by the presentation of our research results in Section 4, which provides an in-depth analysis and discussion of these findings. Finally, Section 5 concludes the article with a summary of our contributions and conclusions drawn from the study.

6.2. State of the art

6.2.1. The digital governance of ports: evolution to the present

Port governance influences numerous sectors such as the logistics chain, economic, management, engineering, etc.[77] . And digital governance is no exception.

Port digitalization seeks to create, through the integration and use of new technologies such as Blockchain, artificial intelligence or the Internet, a work environment where information is more accessible and its use more efficient and intelligent. In such a way that the processes involved in port management can interact with each other in a standardized and unique platform [18]. That is, digital evolution consists of the transformation towards a more digitally interconnected future.

The concept of digital governance is novel in the port system, but widely used by numerous authors in other fields. The concept of digital governance has evolved from the simple use of digital technologies to govern, to a more comprehensive approach that includes the use of these technologies to improve the way governments interact with citizens and businesses [80]. The importance of digital governance mechanisms and principles that enable agile responses in dynamic competitive environments. This suggests that digital governance is not just about using technology for efficiency, but also about using it to be more responsive and adaptable to change [81].

In port history, four significant generations of digital evolution have emerged, each characterized by distinct processes that propel digitalization forward [82]. Figure 6.2 shows the milestones of the digital evolution of ports, from the beginning of this process to the present and what is expected in the near future.

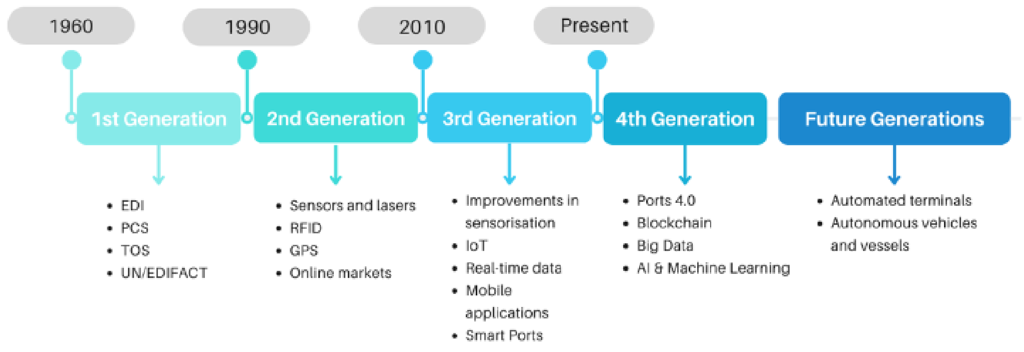


Figure 6.2: Milestones of port digitalization. Source: own elaboration.

Examining the macro-environment of the maritime-port sector, the emergence of digital governance stems from the industry's imperative to adapt to the evolving global landscape. This adaptation entails embracing new technologies and innovations that empower port authorities to optimize their operations, enhance market competitiveness, and demonstrate greater environmental responsibility[22].

The transition towards digital governance and the use of technologies is the basis of industry 4.0 and, therefore, of ports 4.0 and that allow improvements in the speed and efficiency of transport. However, these solutions do not only cover the use of the Internet or Artificial Intelligence. It commenced with seemingly simpler yet equally innovative systems, such as containerization, which revolutionized the industry by standardizing cargo handling and transportation, leading to significant efficiencies and cost savings[22]. This was a maritime milestone that transformed the maritime and logistics industry and served as a basis for ports, today, to use the innovative technologies that are developed.

With the emergence of the Internet, new business formats began to emerge such as social networks, electronic devices or data management in the cloud. These services were making their way to become an essential part of any industry, not being different in the port, where as a result of this the landscape of maritime transport logistics began to change [83].

There are disruptive technologies that significantly impacted the governance of ports such as the Internet, Big Data or Blockchain, these technologies are frequent in the current situation of ports, while others such as fleets or autonomous vessels are expected to have a strong impact in the near future [84].

Digitalization began mainly in ports in Europe and Asia, highlighting Singapore, Hamburg and Rotterdam. It is these ports that, by embarking on digital improvement, managed to take a big step forward in terms of efficiency, cost reduction and increased customer satisfaction [85].

As time progresses and technologies advance, ports worldwide have embarked on this transition, embracing digital solutions to enhance their operations. Latin America stands out in this regard, as digital governance is taking the lead, primarily due to the utilization of open data practices. This contrasts with other countries like Spain, where digital governance adoption may be comparatively slower [86].

Another important case was that of Ghana, in West Africa, where there are several examples of initiatives for the digital governance of its ports. In 2017, a Paperless Port System (PPS) was established to improve the competitiveness, efficiency and transparency of the ports of this country, however, after a year numerous difficulties were denoted that have harmed this initiative [87]. This is an example that the simple implementation of technology without a correct adaptation to port developments does not mean the success of digitalization.

However, the scope and speed of digitization differs greatly between countries and ports. This is due to a number of factors such as governance statutes, the business landscape, and technology investments [88].

The near future bases its advances on automation, not only of terminals but also of ships, vehicles and port machinery, so it is important to know the process and history of maritime-port autonomy [89].

Digital governance: contributions and benefits to ports

Port governance focuses on the use of large volumes of data generated by port systems to obtain valuable information and make strategic decisions, with the use of Big Data and data analysis. Data analytics plays a pivotal role in optimizing resource allocation, forecasting demand, detecting patterns and trends, and enhancing overall decision-making within the maritime-port sector [44].

A significant element of digital governance is citizen participation and transparency: This aspect refers to the use of digital tools to involve citizens in decision-making and improve transparency in port management. This may include citizen participation platforms, public information portals, and interactive communication channels [90].

In terms of benefits, recent studies have highlighted the improvement in operational efficiency through process automation, supply chain optimization and the reduction of waiting times for ships and goods [91].

In addition, digital governance in ports has proven to be an effective tool for strengthening port security, through the implementation of advanced surveillance systems, real-time information exchange and the detection of potential risks [92].

However, implementing digital governance strategies in ports also presents significant challenges [93]. Among them are the need to ensure the interoperability of information systems between the different port actors, the protection of sensitive data and cybersecurity, as well as the management of organizational change required to adopt new technologies and processes.

The challenges associated with digital governance in ports are of many types and must be taken into account.

One of the key challenges is to ensure interoperability between the different systems and platforms used by port actors, such as customs, container terminals, shipping companies and port authorities [38]. The lack of common standards and the heterogeneity of systems can hinder the exchange of information and the efficient coordination of port operations.

Digital governance at ports involves managing vast amounts of sensitive data, from cargo and route information to personal and financial data. Therefore, cybersecurity and data protection are critical challenges [94]. Ports must implement robust security measures to protect systems and information against cyber threats, ensuring the confidentiality, integrity and availability of data.

The adoption of digital governance solutions implies changes in the processes, technologies and organizational culture of ports. Resistance to change, lack of digital skills, and the need to train port staff in the use of new technologies are significant challenges [24]. Effective training programs and change management strategies are crucial to ensure a successful transition to digital governance.

Implementing digital governance solutions in ports can require significant investments in technology infrastructure, specialized software, and human resources [95]. It is critical to evaluate the return on investment (ROI) and financial viability of these projects. Challenges include identifying appropriate funding sources, accurately estimating costs and benefits, and efficiently managing financial resources.

Digital governance in ports involves collaboration between multiple actors, such as port authorities, private companies, governance entities, and port communities [39]. The absence of clear governance and efficient coordination can indeed impede the implementation of digital solutions and hinder collaborative decision-making. Establishing robust governance frameworks and fostering collaboration among the various stakeholders involved are imperative steps to surmount these challenges and facilitate the effective adoption of digital innovations in the maritime-port sector.

There is a digital divide between ports that have access to advanced technologies and those that lack them [96]. This gap may be due to differences in terms of financial resources, technological infrastructure and technical capabilities. To achieve equitable adoption of digital governance in ports, it is necessary to address the digital divide and ensure equitable access to the necessary technologies and resources.

These challenges need to be considered and addressed to achieve a successful implementation of digital governance in ports and make the most of its potential benefits.

In terms of best practices, several studies have highlighted the importance of establishing strong collaborations between public and private actors, encouraging the participation of all stakeholders in the design and implementation of digital solutions, and promoting the training and continuous training of port staff in digital skills.

Digital governance in ports has become an area of growing interest and relevance in the field of port management.

6.2.2. Digital governance: contributions and benefits of End to End Tool

Analyzing the current industry is necessary to be able to adapt to the growing and changing environment in which the world finds itself. Like the subject of this paper, the industry is immersed in the technological revolution marked by digitalization. This allows to improve the operation and development of industrial processes, as well as an increase in productivity and a general reduction in costs and transaction times.

Understanding this, it is understandable that the End to End tool has been used to analyze this area and to be able to establish future strategic lines and action.

However, this tool is highly novel and has been created only recently and that is why it has not yet been applied to industry analysis. So far in this area, analysis tools such as affinity matrix, SWOT matrix, BOT [25], etc., have been used, but they are tools that have certain limitations and that is why the End to End has been created, as an analysis methodology that solves these problems. So, although it has not yet been used in the industry, it is expected that it will be in the coming years when it becomes relevant in this sector [8].

Transport, like industry, has been subjected to the digitalization process, where the development of intelligent and synchromodal transport is currently being sought, thus allowing greater coordination between all modes of transport.

The study tool, in the case of the port area, has been used in issues related to modernization and improvement of efficiency, as well as in the field of sustainability. More specifically, it has been used to analyze the digital evolution of Spanish ports and, secondly, it has been used to analyze the conversion to green ports applied to a specific case study [78]. It is a study methodology that, although it does not yet have a long journey, is allowing an increasingly clear image of the ports to be drawn [8].

In the case of the study of digital evolution, this tool has allowed to take a snapshot of the current state, medium-low, of Spanish ports in terms of digitalization and has determined guidelines to advance in this strategic line, covers the main theme in a national or microenvironment perspective and this has allowed to advance the research to the global macroenvironment [78].

On the other hand, the study of green ports has managed to give another functionality to the tool by applying it to a specific scenario and setting the guidelines to follow to achieve the desired objective and once that is done, extend it to the rest of ports with the same motivations and ambitions [8].

6.3. Methodology and results

The scope and motivation of this work is to determine the short- and long-term future scenario for the Digital Governance of Mediterranean ports through the use of the End to End tool. This system consists of a unique end-to-end management and analysis of information from the beginning of a project, offering a complete functional solution.

The End to End tool is a methodology that seeks to understand a system, analyzing its history from its creation to the present, understanding the economic processes both on a small and large scale, which have made the project evolve. It basically encompasses from origin to completion; Manage the progress of the project by tracking each and every phase of its life.

In this case, the aim is to assess the environment and unique conditions prevalent within the maritime-port sector concerning its digital governance. Furthermore, this tool presents an opportunity to explore potential scenarios for the evolution of digitalization within ports, transcending the present circumstances.

The application of this analytical tool consists of the identification and review of several research factors in order to analyze and then respond strategically to the environment in which the port sector is located. That is, find out what will happen in the near future and use these forecasts as an advantage.

What it seeks is the successful development of a project, establishing the path to reach it and taking into consideration the changing environment in which it is brewing (Figure 6.3).

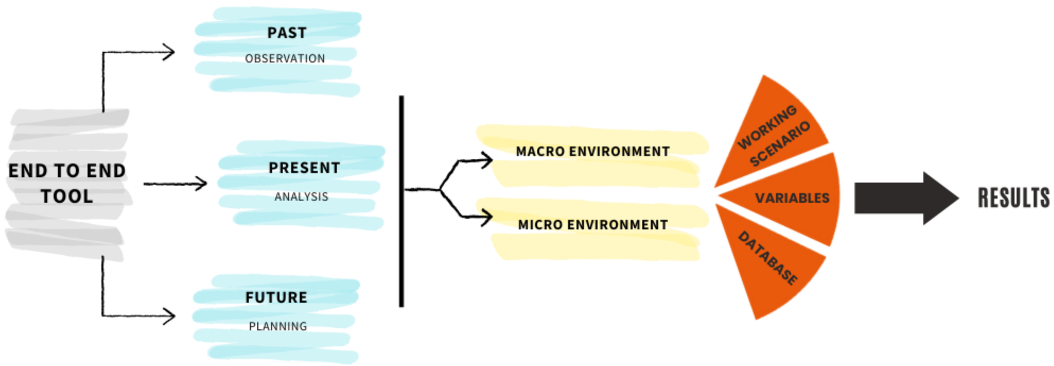


Figure 6.3: Operation end to end tool. Source: (Ramos Velasco et al., 2022).

6.3.1. Approach to the application case

With a comprehensive understanding of digital governance and digitalization in place, the next step is to select the application scenario for the End-to-End tool. This entails carefully choosing the specific context or situation where the tool will be deployed and applied to achieve its intended objectives.

The ports that have been chosen are: Valencia, Barcelona and Algeciras (Spain), Piraeus (Greece) and Genoa (Italy). Some ports of the Mediterranean Sea have been left out of this analysis due to the lack of information and that is why the ones have been taken since they will allow a coherent analysis with useful results. Figure 6.4 shows the situation of the selected ports in the Mediterranean.

Figure 6.4: Selected ports. Source: own elaboration.

6.3.2. Method: Applying End to End Tool

Past

It begins with the results obtained from the observation of the past. It is a comparative table of the 5 case studies on which the following indicators have been evaluated (Table 6.1).

1. Historical experience
2. Main activity
3. Strategy
4. International relations
5. Technological evolution

Table 6.1: Analysis of the past of the selected ports. Source: own elaboration.

INDICATORS	Port of Valencia	Port of Piraeus	Port of Barcelona	Port of Algeciras	Genoa Port
Historical experience	Middle Ages	S. V b.C.	Middle Ages	1894	Middle Ages
Principal activity					
Container	✓	✓	✓	✓	✓
Passengers		✓	✓	✓	✓
Bulk	✓		✓		
Strategy					
Efficiency		✓	✓	✓	
Specialization	✓	✓			✓
Diversification			✓		
Intermodality		✓		✓	✓
International relations	Italy, France, Morocco	Italy, Spain, Turkey	Italy, France, Morocco	Africa, Latin America, Mediterranean Sea, Northern Europe	Spain, France, Greece
Technological evolution	●●●●●	●●○○○	●●●●○	●●●○○	●●●○○

Following this analysis, it becomes evident that historical trends have propelled the evolution and development of ports towards a more efficient, modern, and technologically advanced future. Embracing this evolution is crucial to avoid stagnation, which could result in market loss and company failure. Therefore, transitioning to digital governance aligns with the evolutionary trajectory that ports have historically followed since their inception.

Present

As already mentioned, to understand the present, a SWOT analysis of the port industry of the Mediterranean Sea has been carried out, studying its Strengths and Weaknesses, its internal characteristics, and its Threats and Opportunities, external characteristics (Figure 6.5).

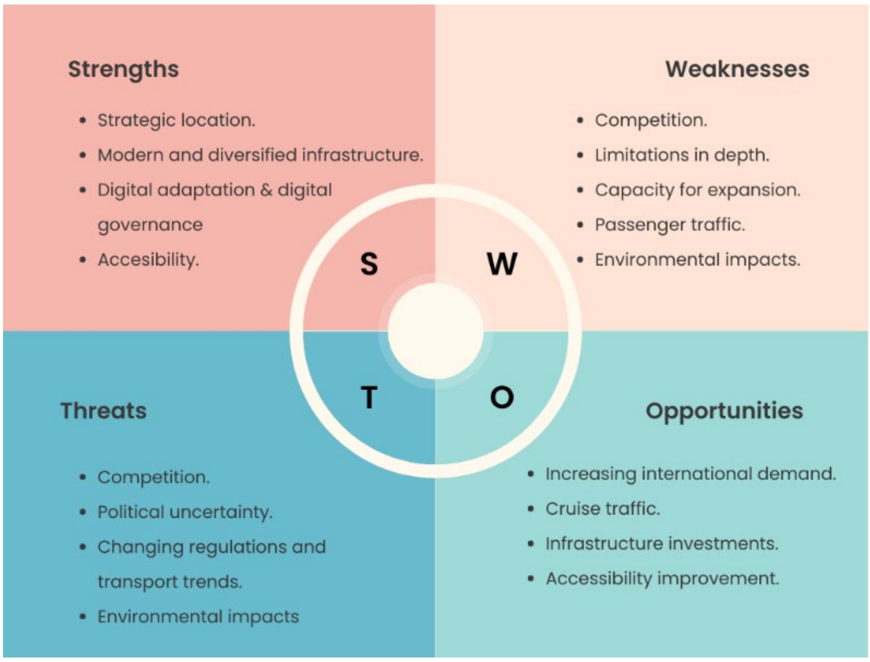


Figure 6.5: SOWT matrix. Source:own elaboration.

With this study, it has been possible to obtain in a rational way the ideas that allow to have an image of the present of the Mediterranean maritime industry. These are:

1. Level of digitalization and digital governance.
2. Environmental impacts
3. Competitiveness and connectivity between ports
4. Infrastructure development

Macroenvironment

This section is developed by selecting data in each port based on their latest published reports, as well as articles and other scientific documentation based on their relationship with the environment in which they are currently located [97], [98], [99].

Finally, it is expected that the maritime industry of the Mediterranean will continue to grow and that these ports will continue to be key pieces in it, given that they are in a constant process of improvement and adaptation to changes in the environment, showing a proactive attitude towards technological innovation and its extension to administrative departments to achieve complete digital governance, requirement to face present and future challenges in a transparent, efficient and connected way in real time. In addition, they are working hard to try to reduce their environmental impacts and achieve demanding environmental standards, a promise that, today, seems difficult, but is necessary to generate the pressure that causes change. This is intended to ensure that ports continue to be an essential part of the development engine of the countries where they are located.

As an example, Table 6.2 is presented below, which forms the model of the database to be taken.

Table 6.2: Database. Source:own elaboration.

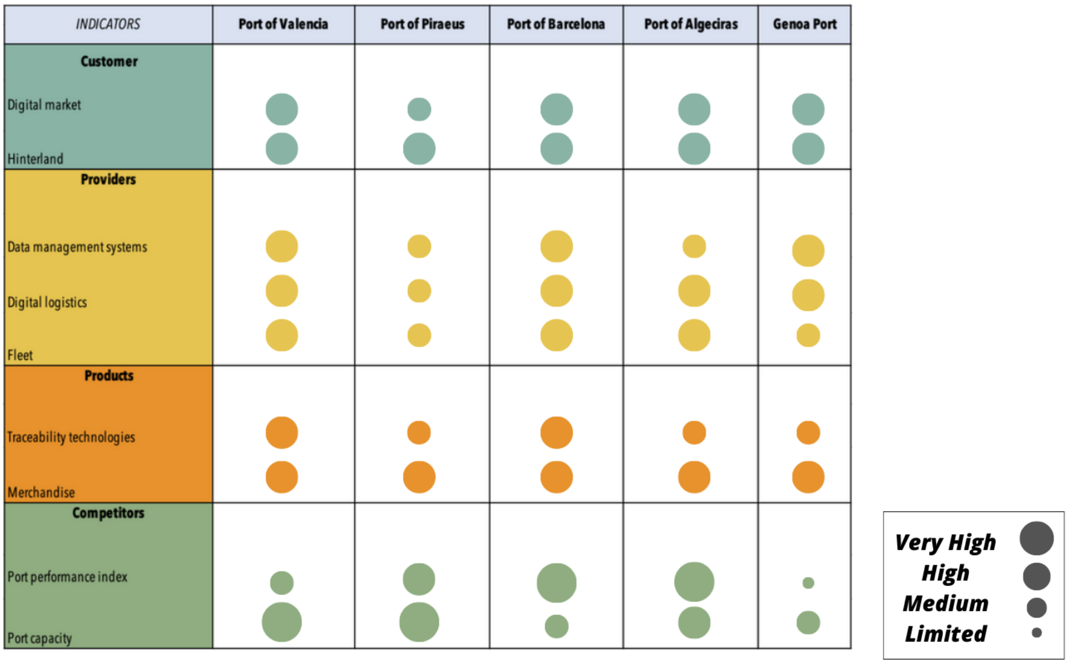
Category	Subcategory	ID	Indicator
Past	Historical experience	Pa_1	Historical experience
Past	Principal activity	Pa_2	Principal activity
Past	Strategy	Pa_3	Strategy
Past	International relations	Pa_4	International relations
Past	Technological evolution	Pa_5	Technological evolution
Present - Macro Environment	Economic	MaE_1	Cargo volume
Present - Macro Environment	Economic	MaE_2	Number of berths
Present - Macro Environment	Economic	MaE_3	Infrastructure investment
Present - Macro Environment	Economic	MaE_4	Total traffic
Present - Macro Environment	Institutional	MaI_1	Government investment
Present - Macro Environment	Institutional	MaI_2	Political stability of a country
Present - Macro Environment	Institutional	MaI_3	Regional competitiveness
Present - Macro Environment	Institutional	MaI_4	Transparency
Present - Macro Environment	Institutional	MaI_5	Protection of the national port brand
Present - Macro Environment	Sociocultural	MaSC_1	Employability
Present - Macro Environment	Sociocultural	MaSC_2	Employee training programmes
Present - Macro Environment	Sociocultural	MaSC_3	Gender Inclusiveness
Present - Macro Environment	Sustainability	MaS_1	Greenhouse gas emissions
Present - Macro Environment	Sustainability	MaS_2	Energy consumption
Present - Macro Environment	Sustainability	MaS_3	Water consumption
Present - Macro Environment	Sustainability	MaS_4	Biodiversity and habitat
Present - Macro Environment	Sustainability	MaS_5	Reduction of water consumption (compared to 2019)
Present - Macro Environment	Sustainability	MaS_6	Reduction in energy consumption (compared to 2019)
Present - Macro Environment	Technological	MaT_1	Use of ICTs
Present - Macro Environment	Technological	MaT_2	Use of AI
Present - Macro Environment	Technological	MaT_3	Use of Digital Twins
Present - Macro Environment	Technological	MaT_4	Use of chatbots
Present - Macro Environment	Technological	MaT_5	Metaverse
Present - Macro Environment	Technological	MaT_6	Digital competitiveness
Present - Macro Environment	Technological	MaT_7	Ports using GIS
Present - Macro Environment	Legal	MaL_1	Code of Ethics for Port Agencies
Present - Micro Environment	Legal	MaL_2	IMO Compendium Regulations
Present - Micro Environment	Legal	MaL_3	Corruption Perception Index
Present - Micro Environment	Customers	MiCu_1	Digital market

Present - Micro Environment	Customers	MiCu_2	Hinterland
Present - Micro Environment	Suppliers	MiS_1	Data management system
Present - Micro Environment	Suppliers	MiS_2	Digital logistics
Present - Micro Environment	Suppliers	MiS_3	Fleet
Present - Micro Environment	Products	MiP_1	Traceability technologies
Present - Micro Environment	Products	MiP_2	Merchandise
Present - Micro Environment	Competitors	MiCo_1	Port performance index

Microenvironment

The analysis of the microenvironment is composed of indicators whose results are qualitative, unlike many of the macroenvironment, which could be defined by data and statistics. The results of this variable are shown in the following table (Table 6.3).

Table 6.3: Microenvironment. Source: own elaboration.



Based on the analysis conducted, it is evident that port development is indeed trending towards increased digitalization and automation of container loading and unloading processes. Furthermore, there is a growing inclination towards greater implementation of monitoring and data management technologies within port operations. These trends underscore the industry's commitment to enhancing efficiency, optimizing resource utilization, and leveraging technology to meet evolving demands and challenges.

Ports are focusing on improving their efficiency and management capacity through technology and innovation. The inherent future of ports lies in continuous improvement and technological implementation, largely driven by competitive pressures. To optimize their operations and maintain a prominent position in the global maritime market, ports must transition to fully digitized governance processes. This shift is imperative to meet the evolving demands of the industry and ensure sustained competitiveness in the international arena.

6.4. Analysis of results

Firstly, it has sought to analyze the port governance through the indicators studied, for which we have analyzed more specifically the level of transparency, its ethics, degree of training of employees, as well as the political stability and level of corruption of the countries where they are located, since they directly affect the form of governance of these.

Figure 6.6 shows that both in terms of transparency and ethics, the ports of the Mediterranean environment are very well positioned, they have established effective port management systems that promote transparency and ethics in their operations. This is achieved through the implementation of clear policies and standardized procedures that ensure fairness in decision-making. In addition, Mediterranean ports have committed to maintaining high ethical standards in their business activities, including the fight against corruption and bribery. These practices have earned ports the trust of users and operators, solidifying their role as vital shipping and logistics hubs in the region. However, in relation to this it is difficult to understand what will happen in the future, because, although the great importance of ports in these issues is demonstrated, there is no force external to them that encourages or generates pressure to continue developing.

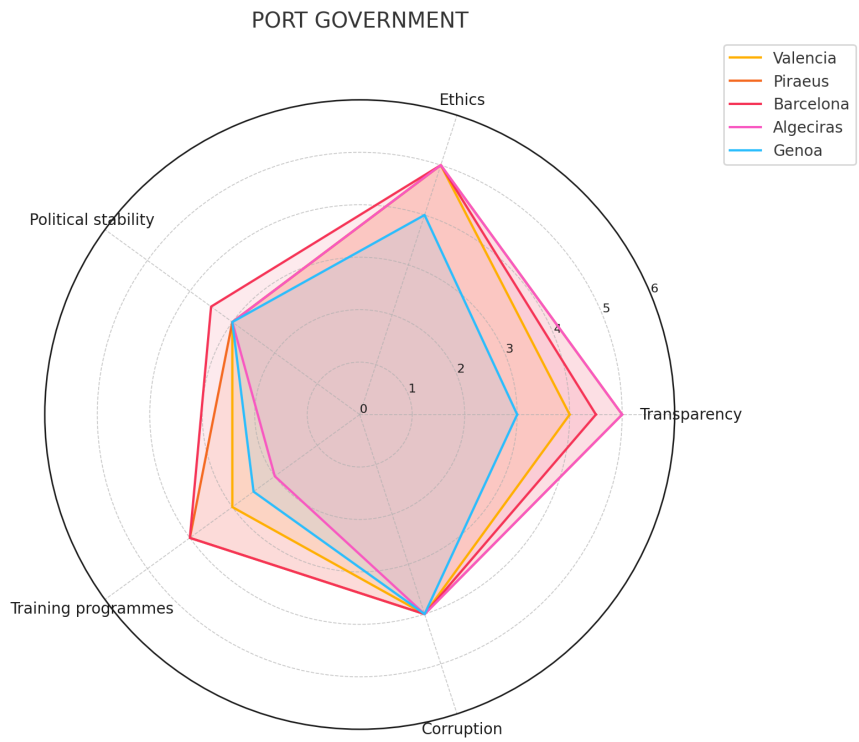


Figure 6.6: Port governance analysis. Source: own elaboration.

From this analysis, the importance of the security and honesty of the business is deduced, as well as the need for protocols and constant training programs for workers or reskilling, to move from traditional governance to a more innovative one focused on digitalization, which is becoming especially important as can be seen in the following figure and it is undoubtedly that it will continue to develop in the coming years.

Figure 6.7 shows the degree of adoption of the main digitization technologies in the 5 case studies.

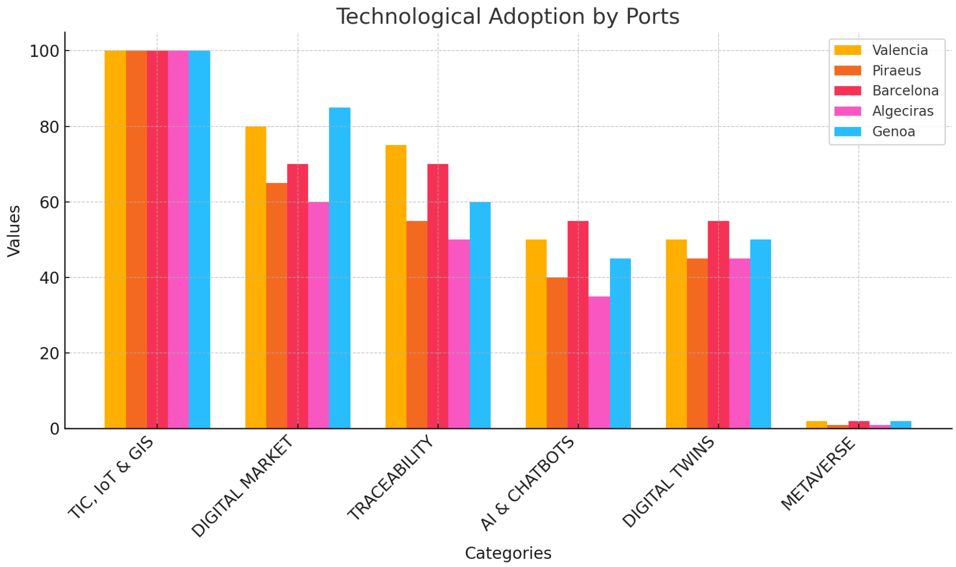


Figure 6.7: Digital analysis. Source: own elaboration.

From this analysis, it is clear that the maritime industry is embracing new technologies and fostering a culture of innovation by studying, developing, and implementing them within the sector. In addition, due to the current global hyperconnection, the fact that ports are advancing on common issues means that they are almost certainly struggling to break the biggest barrier that hinders the maritime industry, which is the disparity in process management, this derives in the already known and final point of this research, Digital governance, a process that with its future reach, will solve all the problems associated with disinformation and lack of homogenization of processes, as well as everything that they entail. These differences and inefficiencies will disappear as technologies and Artificial Intelligences begin to establish protocols and process standardization programs that allow an interoperable maritime industry worldwide.

Next, the information pertaining to investment in ports, as indicated by governance investment and infrastructure indicators, has been collected, revealing disparities between them (Figure 6.8). Nevertheless, it's evident that over the years, all the case studies have been striving to adapt to the expanding international trade and global logistics chains to maintain their competitiveness in the Mediterranean region. It is intuited that this practice will continue with the same growing trend due to the need to improve ports either physically or digitally, for which access to economic resources is necessary.

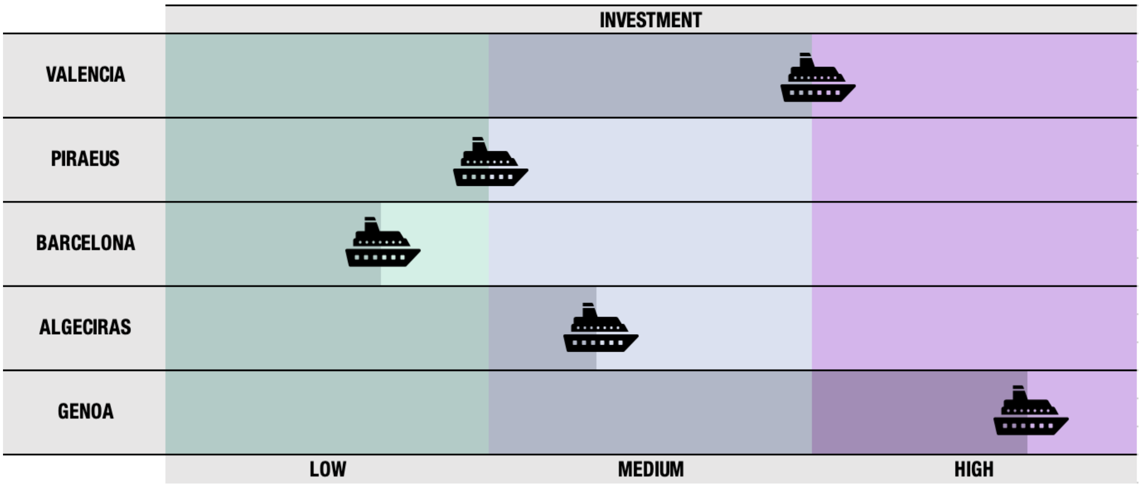


Figure 6.8: Investment analysis. Source: own elaboration.

This, added to the previous analyses, suggests that access to financing is essential to maintain a position in the market, adapting its work and governance methodologies to the digital world in which the current global panorama is immersed, and which will continue to develop in the coming years.

Another crucial aspect gleaned from the analysis via End to End is understanding the success of port businesses and whether this trend will persist with the pursuit of full digitalization of their administrative departments (Figure 6.9). For which indicators have been addressed that have certain features in common, more specifically, adaptation to the environment, keeping business protection as a priority.

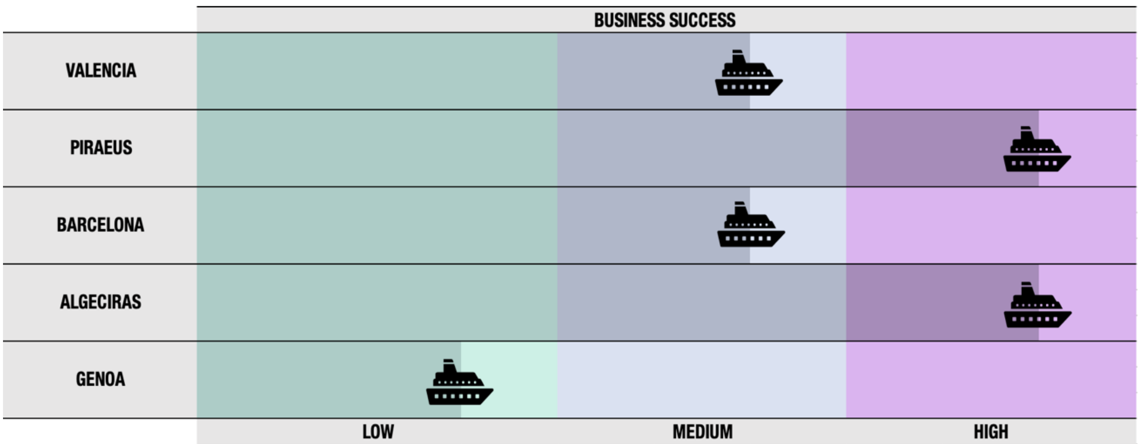


Figure 6.9: Business success analysis. Source: own elaboration.

The study is expected to continue designing and implementing public policies and promoting private initiatives for the adoption of digital governance and thus improve the competitiveness of the sector with greater performance, support and capacity of ports.

The overarching objective of this research is to analyze the present and future state of digital governance. All preceding diagrams have contextualized their data in relation to this parameter, which is logical given that the governance of a port serves as its central function. That is, without governance there is no port and therefore, its form of application must be constantly adapted to the environment and hence ports are committed to its digitalization.

Figure 6.10 shows the fundamental pillars of port digital governance.

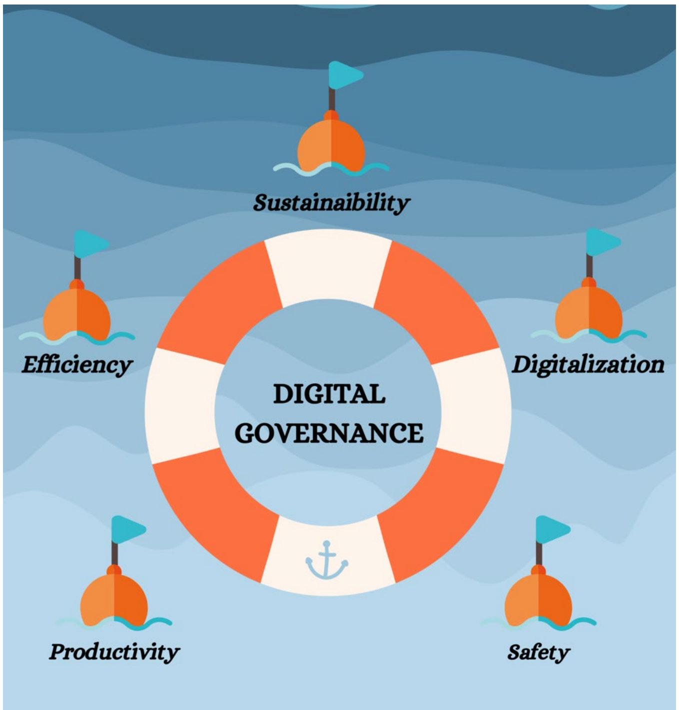


Figure 6.10: Fundamental pillar digital governance. Source: own elaboration.

The evaluation has considered aspects such as transparency in management, accessibility of information, data security, port operation and efficiency in the management of digital resources. Therefore, it has been determined that the port that currently has the best digital governance is Valencia, followed by Piraeus, Barcelona and Algeciras with a very comparable management and, finally, that of Genoa (Figure 6.11).

It is important to remark this classification is not static but is anticipated to evolve as competition drives the endeavor to enhance digital governance in each port. Consequently, this assessment serves not only as a means to identify leaders in this domain but also as a catalyst to inspire and stimulate continuous advancement and enhancement of digital governance within the global ports market.

Figure 6.11: Ranking of ports. Source: own elaboration.

The success of digital governance in the future will depend on the commitment and collaboration between the agents involved, whether governances, port operators, shipping companies or technology providers. Its interoperability will make it possible to make the most of the opportunities offered by digital transformation, improving efficiency, competitiveness, security and trust in the port sector (Figure 6.12).

The future of digital governance looks exciting and promising and is contingent on adaptability and strategic vision to address developments and manage them effectively for the benefit of all stakeholders.

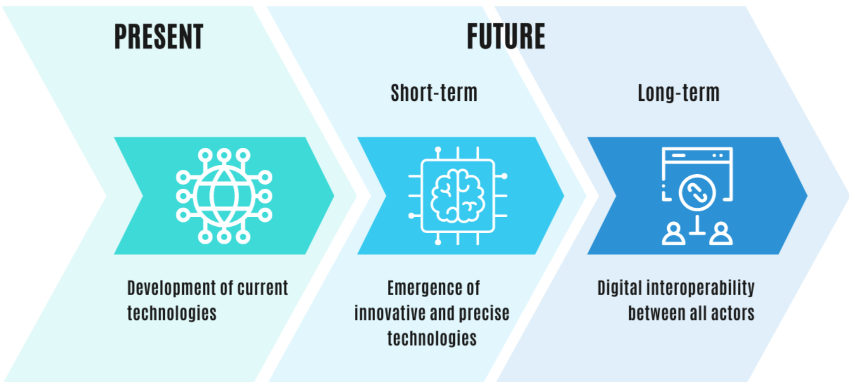


Figure 6.12: Future of digital governance. Source: own elaboration.

Finally, the internal analysis of the port environment reveals common characteristics among the studied ports. All of them have their own digital platforms for electronic information exchange among maritime agents. Although the ports are connected by European rail corridors, each has unique features in its area of influence, with access to diverse markets and customers.

Regarding suppliers, the ports have implemented advanced data management and digital logistics systems, such as the Navis terminal management system, to optimize container loading and unloading processes. Additionally, they have a wide variety of shipping service providers, including globally recognized companies like Maersk, MSC, and CMA CGM.

In terms of products, the ports are highly competitive and adopt innovative cargo and container monitoring technologies, with Valencia and Barcelona leading in this aspect.

Regarding competition, port performance is assessed in categories such as operational efficiency, infrastructure, capacity, and service quality. The best-performing ports in these areas are Algeciras and Barcelona, followed by Piraeus, Valencia, and Genoa.

In summary, port development focuses on digitization and automation of processes, as well as the implementation of monitoring and data management technologies. This requires internal process adaptation and high modernization to maintain competitiveness. Ports aim to enhance efficiency and management capacity through technology and innovation, responding to competitive pressures in the international maritime market. The transition to fully digitized port governance processes is crucial to maintain a relevant position in the market.

6.5. Conclusions

Firstly, there has been a clear need to implement e-governance policies and transparency in port management, in order to increase efficiency and improve the quality of services offered to users. Likewise, it has been proven that there is a significant disparity between the different ports in terms of the implementation of management, cybersecurity and data protection measures, which puts at risk the integrity of the logistics chain, systems and user privacy.

In addition, it has been observed that ports that have implemented advanced technological solutions and efficient digital management have managed to improve competitiveness and increase their attractiveness as a tourist destination and as a place for the development of economic activities related to the transport of goods. On the other hand, the need to establish clear and updated regulatory frameworks has been identified to guarantee efficient and secure management of data and computer systems in ports.

With this, the following ideas have been clarified that have become statements for the future development of digital governance:

Public policies and private initiatives are essential to foster the adoption of digital governance and enhance the competitiveness of the sector.

Receipt by the ports of fiscal incentives and promotion of public-private collaborations with continuous training and reskilling programs.

Proclamation and adoption of standards and protocols for the interoperability of port management systems.

Promotion of a business culture that promotes innovation and adoption of digital technologies for the correct management of data or infostructure.

Access to necessary financing due to the presence of high costs associated with the implementation of the measures in question.

The ultimate goal of digital governance should be none other than to achieve maximum efficiency and productivity, based on sustainable measures to respect the environment and maintaining a level of security in accordance with the highly established standards of information management; The most critical and strategic resource today, indispensable for the development of any sector.

The development of these premises will lead to the future success of digital governance that will depend on the commitment and collaboration of agents, taking advantage of the opportunities offered by digital transformation, improving the efficiency, competitiveness and confidence of the port sector. Promising future as long as the adaptation and strategic vision are managed properly and without forgetting the premises necessary for a correct development and collected in Figure 6.13.

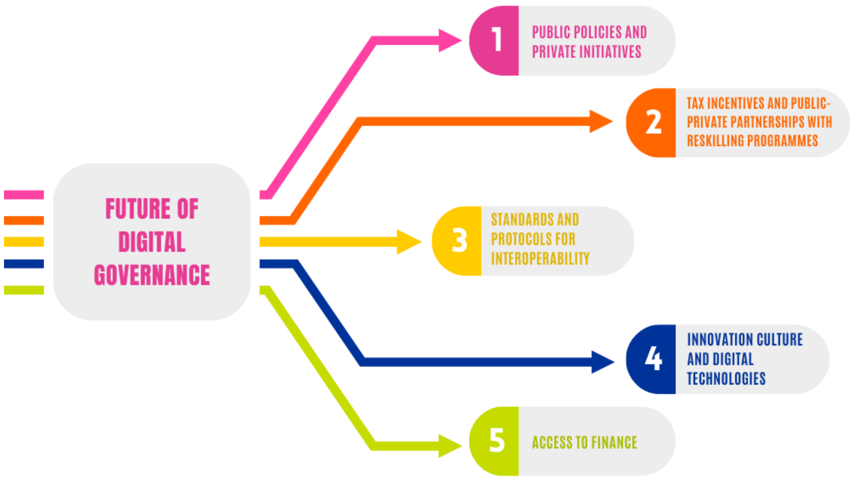


Figure 6.13: Keys to the future development of digital governance. Source: own elaboration.

In the future, it is probable that we will want to delve deeper to a broader level in order to continue with the study trend. It is to be hoped that the tool will soon be used again to analyze an even more international environment, consistent with the present importance of globalization. To do this, it will be necessary to look for ways and tools to overcome the limitations that, today, restrict the available information, such as the increasingly developed Artificial Intelligences or other types of tools that allow greater communication and transparency with the world's Port Authorities.

Finally, as the conclusion of the research of the study ports, it has been determined that the level of development of digital governance is higher in Valencia, followed by Piraeus, Barcelona and Algeciras, practically on par and finally that of Genoa. All of them are ports that are still classified with state-of-the-art and admirable digitized administrative systems worldwide, which reflect that the classification is dynamic and will change as ports incorporate new and innovative management systems. After this, it is concluded that digital governance will continue to develop as a key piece, not only in these ports but in all those who want to stay in the current changing global landscape.

Abbreviation list:

EDI: Electronic data interchange

PCS: Port community system

TOS: Terminal Operator system

ONU/EDIFACT: Electronic Data Interchange for Administration, Trade and Transport.

RFID: Radio Frequency Identification

GPS: geographic position system

IoT: Internet of things

7. NEW VIRTUAL PORT ECOSYSTEM

This chapter presents the accepted manuscript of RA3 that has been published in a peer-reviewed and indexed journal:

Vaca-Cabrero, J., González-Cancelas, N., Orive, A. C., & Flores, F. S. (2024). **Metaverse in ports through an affinity diagram**. *Journal of Infrastructure, Policy and Development*, *8*(5), 3303. https://doi.org/10.24294/jipd.v8i5.3303

Abstract: A metaverse is an environment where humans interact socially and economically as avatars in cyberspace, which acts as a metaphor for the real world but without its physical or economic limitations. Many people use this new technology to connect with others, exchange content or discover new hobbies. Unlike other virtual worlds, the metaverse offers an online world that can be shaped. For the ports of the Spanish port system, it is intended to determine the new virtual port ecosystem that could be developed in the short term through an affinity diagram, which is a diagram that is used for the organization of ideas provided by a group on a complex problem that is held in a specific area, in this case reaching metaports in the port system. The main conclusion is that to advance on this concept the new operating models and customers and services, are the blocks where the greatest efforts will have to be made.

7.1. Introduction

The Metaverse is a virtual world, one that you can connect to using a series of devices that will make you think that you are really inside it, interacting with all its elements. It will be like actually teleporting to a whole new world through virtual reality glasses and other complements that will allow us to interact with it. [100]

The metaverse is not intended to be a fantasy world, but a kind of alternative reality in which you can do the same things you do today outside your home, but without leaving your room.[27]

The metaverse is a term that has recently gained popularity and generated a great deal of enthusiasm in the technology arena. In its most basic form, the metaverse refers to a shared virtual space in which people can interact with each other and with digital objects in real time. It is a virtual world in which multiple users can coexist and engage in a variety of activities, from working and learning to socializing and playing games. Unlike virtual reality and immersive experience, the metaverse is a persistent and constantly evolving digital representation of the real world, rather than an isolated experience [101].

Immersive experience encompasses a wide range of technologies and techniques that seek to create a sense of presence and full participation in an environment. Although virtual reality is a common form of immersive experience, it can also include other technologies, such as augmented reality (AR) and mixed reality (MR).

Immersive experience seeks to integrate digital technology into the physical environment, overlaying virtual objects and elements on the real world or creating a fusion between the two.[102].

Unlike VR, the immersive experience does not necessarily require a completelymetaverse, but can enhance the existing reality by adding interactive digital layers [103]. Thus, the arrival of the Metaverse will positively impact many sectors of the economy, starting with the leisure and entertainment sector, as we already see in video games and sports; also in the education sector, which has great potential for growth in this new digital reality [104]. Aditionally, a significant growth in the use of the Metaverse by digital commerce is on the horizon, supported by the Blockchain and NFTs, which will differentiate it from Ecommerce as we know it [105].

The metaverse is a broader concept and encompasses multiple interconnectedmetaverses, while virtual reality focuses on providing an immersive experience in a single environment[27].The metaverse is a constantly evolving virtual space in which users can interact and create experiences in real time. Artificial intelligence (AI) plays a fundamental role in the development and expansion of this digital universe, enabling the creation of more realistic and engaging worlds.[29].

The metaverse and logistics are two concepts that have a close relationship. Especially when viewed from the point of view of how logistics could play a role within the metaverse [106].

Indeed, in the context of the metaverse, logistics could play a role in managing the distribution of digital goods and services within that virtual space. For example, in a metaverse where people can buy and sell digital objects, a logistics infrastructure would be needed to manage transactions, store digital objects, and facilitate their delivery to buyers [107].

Phygital is an acronym for the words "physical" and "digital" and refers to the seamless integration of physical and digital experiences. It's a concept that's becoming increasingly important as businesses look for ways to create more engaging and personalized experiences for their customers [108].

The concept of phygital can be applied to logistics in a number of ways. For example, businesses can use augmented reality (AR) to allow customers to see what products would look like in their homes before they buy them. They can also use virtual reality (VR) to allow customers to try on clothes or beauty products virtually. Companies can also use phygital technology to improve the efficiency of their logistics operations. For example, they can use artificial intelligence (AI) to automate tasks, such as inventory management or route planning [109].

In addition, another relevant fact about the metaverse and logistics is that the latter could be relevant in terms of the physical infrastructure needed to support the operation of the metaverse. This could include servers, data centers, network connections, and other logistical elements needed to ensure proper connectivity and performance of the metaverse [110].

While a fully immersive and interconnected metaverse is still years away, mobility stakeholders can already capture the real business value of the technologies designed to make it possible [111].

Almost anything that can be done in the real world can be translated into the metaverse, as long as it fulfills its intended potential. However, new companies and organizations are appearing every day, inventing ways to be present in this fashionable virtual universe, making this idea more and more real [112].

Transportation companies also have their space within the metaverse, as they could basically offer the same services as in the real world [113].

So far, technology has made it possible to "democratize" and expand the possibilities of the supply chain around the world. With the advent of pandemic, process automation, the use of robotics, blockchain and other innovations have simplified operations [21].

More importantly, their use has made companies truly put the user at the center of all efforts, as all of these processes are aimed at empowering and personalizing the consumer experience [114].

Research on the use of metaverses in ports globally is an emerging field, and research gaps can evolve rapidly. However, some potential research gaps in this area correspond to the following areas: Human-Metaverse Interaction in Port Operations, Security and Privacy in Metaports, Socioeconomic Impact, Integration with Existing Infrastructures, Adaptation to Technological Changes, Standardization and Regulations: and Stakeholder Engagement

The most important questions that should be able to be solved with the course of this research should be, among others, how the introduction of metaverses affects human interaction in port operations, and what are the best practices to facilitate a smooth and efficient transition from traditional operational practices to metaverse environments. In addition, with respect to privacy and security, it should be possible to determine what the specific security and privacy challenges are. Regarding the long-term socio-economic impact of the introduction of metaports in port communities, it should be possible to determine how it will affect employees, businesses and local economies. Another concern is associated with the rapid technological changes associated with the implementation of metaports and the possibility of adapting port environments to achieve a successful transition. It will be of paramount importance not only to determine how the various stakeholders, such as governments, port authorities, businesses and civil society, can be effectively involved in the creation and management of metaports, but also what are the specific challenges in cross-sector collaboration in this context.

7.2. Review of Literature

The metaverse is a term that refers to a shared virtual universe, simulated by a computer, in which users can interact and experience a virtual reality in real time. This experience can be achieved through virtual, augmented, or mixed reality and can include 3D representations of people, objects, and environments. The goal of the metaverse is to create a virtual world in which users can interact and experience an alternative reality to real life [115].

In the context of this research, the metaverse can be defined as a three-dimensionalmetaverse that simulates the physical space of a port and its operations. This environment allows the immersive interaction of users, to participate in activities related to the transport chain, port management, port operation and port operations. The ports metaverse includes elements of remote collaboration, real-time visualization, and the incorporation of emerging technologies.

As an example of this, we can think of a scenario where a port metaverse facilitates efficient management between different actors, such as suppliers, carriers and customs authorities, by allowing them to interact in ametaverse to coordinate and optimize the loading and unloading of goods. Worker avatars can access real-time data on container location, shipment status, and storage capacity, enabling faster and more accurate decision-making. The metaverse could even simulate complex situations, improving daily operations while contributing to greater resilience to unforeseen events, such as congestion at docks or unexpected changes in demand.

The metaverse has advanced significantly in several sectors, including video games, entertainment, education and training, business and commerce, and virtual reality. However, in recent years, the sector that has experienced the greatest advancement in the metaverse is video games and entertainment, thanks to the popularity of online games and the growing demand for immersive experiences. New applications are also being explored in other sectors, such as education and training, where metaverse solutions are being developed to improve the effectiveness and efficiency of teaching. In the future, we are likely to see further progress on the metaverse across a wide range of sectors [116].

The metaverse is one aspect of digitization. Digitalization refers to the process of transforming analog processes, information and products into digital format. The metaverse is a form of digitization in which a virtual universe is created that allows users to interact in a digital environment in real time [117].

In the metaverse, virtual reality and artificial intelligence combine to create an online experience in which users can participate in virtual activities, such as playing games, participating in conferences, doing business, etc. In this sense, the metaverse is considered an advanced form of digitalization that offers a more immersive and participatory virtual reality experience than other forms of virtual reality [118].

The metaverse is a form of digitization that focuses on creating a real-time virtual experience that allows users to interact in a digital environment [119].

The metaverse is also influencing the supply chain in various ways. This includes demand planning, where different demand scenarios are simulated and analyzed to enable companies to make informed decisions about production and supply chain planning [120]. Additionally, it is utilized for supply chain simulation to assess its efficiency, identifying bottlenecks and solutions to enhance overall effectiveness [121]. Real-time collaboration is another application, allowing companies to collaborate more efficiently with their supply chain partners, sharing information and making collective decisions [122]. Furthermore, companies can leverage the metaverse to effectively showcase their products to customers, gaining valuable feedback and making informed decisions about production.

The metaverse is beginning to have an impact on the supply chain, offering new ways of planning, collaborating, and demonstrating products that improve supply chain efficiency and effectiveness [41], [122].

The supply chain in the digital age has become a broad concept based on systems, analytics and tracking of goods, vehicles and other assets through what we know as IoT (Internet of Things), bringing significant improvements in the operation of supply chains [123].

Technologies such as predictive analytics, a statistical technique that analyzes actual historical and current data to make predictions about unknown or future events, improve visibility into the movement of goods, and robotics help DCS (Distributed Control System) keep pace with supply chain management in the digital age [124].

Technological trends in the supply chain encompass various developments. Notably, there is a growing emphasis on network-centric visibility [125] to enhance transparency. Integrating the Internet of Things (IoT) with application processes is becoming pivotal for streamlined operations [126]. Scenario-based planning [127] is emerging as a strategic approach, while the implementation of IoT, smart routing, and predictive analytics is shaping the future of supply chain dynamics [128]. Mobile robotics is inducing transformative changes in Distributed Control Systems (DCS) [129], and the anticipation of Cloud Transportation Management Systems (Cloud TMS) breaking down information silos signals a paradigm shift in information management [130].

Many application categories are adopting Cloud TMS implementation as a natural solution because it transforms transportation management from an internal activity into a process that can easily connect with third-party logistics providers [131].

Some of the risks involved in the metaverse:

- Hacking headphones and microphones [132].
- Biometric data theft [133] [134].
- Behavioral data [27].
- Compromised Privacy [111].

The metaverse is a project under permanent construction. Just as the Internet has been in the last decades [135].

Maritime traffic does not want to be oblivious to the potential of the metaverse metaverse. In the maritime environment, the advantages and applications of the metaverse are being exploited, especially in improving efficiency and for the collaboration of the supply chain, of which ports are just another link. Some of the uses of the Metaverse applied to maritime traffic would be:

- The metaverse enables the creation of customized virtual port environments, allowing the simulation of specific situations and the practice of specific skills. This allows for more customized simulation and training tailored to the needs of the ports [104].
- As a tool for collaborative work, the metaverse can accomplish much more than simply bringing teams together in a unified space. The metaverse promises to bring new levels of connectivity to the virtual work world, allowing people working in the supply and transportation chain associated with ports to interact in real time with digital twins, explore different environments securely, and share information like never before [27].
- Regarding maritime traffic. The metaverse will offer simulations with different operations and scenarios, to test them before opting for one or the other. This type of hypothetical simulations is called virtual twins [100].
- With data and analysis in the metaverse, different shipping route schedules could be simulated and their efficiency evaluated. This could help port professionals to optimize shipping routes. In addition, it will also be possible to reduce transportation costs, minimize delivery times and improve the sustainability of logistics operations [136].

Improving efficiency in ports is an element of constant study and improvement, with the help of the metaverse real time information about maritime traffic and activity in the port can be visualized, furthermore the simulation of different scenarios allows planning and managing port capacity by modeling port capacity, optimizing port capacity and improving efficiency in terms of time and cost [104].

The metaverse has numerous artificial intelligence and machine learning tools that can be employed to improve port planning and capacity, although no specific tools exist to date, simulation platforms can be used to test different scenarios and assess their impact on capacity [27].

With the metaverse, real-time data can be employed that allows companies to manage and process large volumes of data in motion, therefore it can be employed by the port environment to find real-time solutions, as it allows real-time data flow between applications and systems [137].

Data in Motion refers to data that is generated in real time and constantly moving between systems, applications and devices. This data in motion includes everything from financial transactions and sensor data to social media messages and server logs, allowing for real-time solutions, identifying problems in real time and attempting to respond to them almost automatically and improving efficiency [138].

In the port environment, the metaverse can be primarily fueled by various technological tools. Project management software acts as a connector, facilitating collaboration among teams and enabling all organization members to prioritize crucial tasks [137].Virtual reality platforms, defined as environments where technology generates realistic images and simulates presence, offer new possibilities for interaction and visualization [104]. Management information systems extract internal system data and summarize it into useful formats, such as management reports, supporting activities and decision-making, allowing port stakeholders to share and collaborate on documents in real-time [139]. Communication tools, enabling the transmission and reception of messages, play a crucial role in connecting and effectively coordinating participants within the port metaverse [140].

The metaverse in the port environment can be powered mainly by the following tools (Figure 7.1)

Virtual reality platforms: They allow users to collaborate in real time in a virtual environment, which can be very useful in the context of ports.

Online communication tools: Such as chat, email, and video conferencing, which allow users to communicate and collaborate in real time from different locations.

Project tools: Like Trello, Asana, or Slack, which help teams coordinate and collaborate on projects in real time.

Information management systems: Such as SharePoint or Google Drive, which allow you to share and collaborate on documents in real time.

Figure 7.1: Tools for enhance real-time collaboration. Source: own source.

There are several tools that can be used to enhance real-time collaboration in ports aided by the metaverse [141].

These tools can help improve efficiency and productivity in port collaboration aided by the metaverse [142].

The metaverse is considered the next evolution of the Internet, it could be expressed as a 3D Internet, persistent three-dimensional spaces that integrate the virtual and real world. A different way of interacting with users and companies through avatars, the equivalent of a user profile in a social network. No one now doubts the benefits and importance of social networks for companies, so it is difficult to doubt their natural evolution [104].

Based on the fact that the metaverse functions as a virtual complement to the real world, it can be understood that digital twins can be part of the metaverse [143]. For example, the information of the transport in which we travel (car, plane, boat ...) acquired through the sensors feeds its digital twin with real-time data and at the same time it allows us to publish the information we want to share, such as geolocation, weather conditions, camera view in our favorite social network within the metaverse, associated with our representative who is the avatar [105].

3D models can help the visualization of information in ports, the metaverse collaborates to increase our value chain, increases competitiveness, the differentiation of our products and their perception of quality [104].

Virtual reality, artificial intelligence, interactivity, blockchain, IoT, digital twin... the metaverse of logistics, the next revolution born from the internet, poses new challenges for the port environment. Born in the gamer environment, the metaverse has spread to all facets of social and business life, redefining the scenario of the physical and the virtual, where both represent two sides of the same coin [100].

The metaverse is a broad concept that can exist without the need for AI. In fact, there are some metaverses that don't use AI at all.

However, AI has the potential to significantly improve the metaverse experience. For example, AI can be used to generate user-generated content (UGC), create realistic virtual characters, and provide more personalized user experiences.

Consequently, while AI is not central to the existence of a metaverse, it is a technology that has the potential to transform the way we interact with these virtual worlds.

Port activity has been entering the virtual world for some time now, although so far not with avatars but with simulation programs for augmented reality. The metaverse is more than just an online representation, and the key lies in the digitalization of port profiles and processes linked to port operations, as well as in the interoperability of future scenarios [144].

For port operators, it represents a further step in the digitization of the sector, including a multisensory factor perceived by the user through the use of peripheral devices. Thus, the combination of technologies that have already been used separately (blockchain, virtual reality, artificial intelligence or IoT) and the application of 5G achieve the immersion of the user in port operations [104].

The implementation of metaports in port environments faces significant challenges that require detailed attention. One of the key challenges lies in adapting traditional port infrastructures to the technological and virtual requirements of metaports. Interoperability between existing systems and new technologies presents obstacles, as well as the effective integration of real-time data from multiple sources, as outlined in [145].

Recent research highlights that another critical challenge is acceptance and adoption by port stakeholders. The introduction of metaports implies a significant cultural and operational change, which could generate resistance and require effective organizational change strategies, it is appreciated that the necessary cultural change is not permeating organizations [27].

When talking about anymetaverse, security and privacy are constant concerns. Protecting sensitive data and managing cybersecurity are critical challenges that need to be addressed to ensure user trust and the integrity of port operations in the metaverse [146].

These challenges are crucial because they directly affect the efficiency and feasibility of implementing metaports in the port system. The research focuses on addressing these challenges proactively, proposing practical solutions and innovative strategies. Through a comprehensive approach, it seeks not only to overcome technical and operational barriers, but also to promote a smooth and successful transition to virtual port environments, thus maximizing the potential benefits for all parties involved and that the metaverse can become a reality in Spanish ports.

7.3. Materials and methods

The following diagram (Figure 7.2) shows the different phases of the methodology to be used:

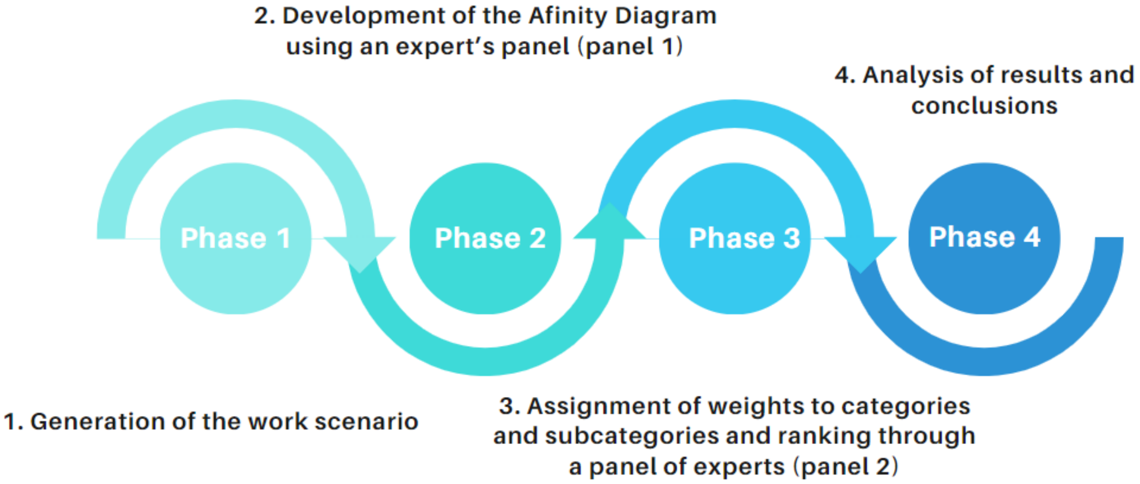


Figure 7.2: Methodology scheme. Source: own source.

An affinity diagram, also known as an affinity map, is a visual tool used to organize information (Figure 7.3). By classifying data or ideas by common themes, a team can develop new ways to process complex problems [47].

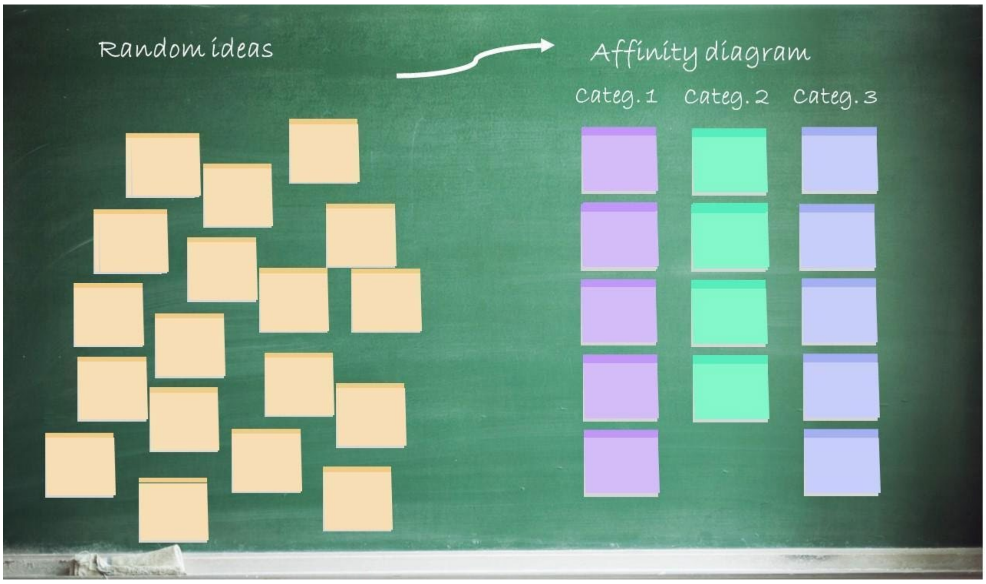


Figure 7.3: How the affinity diagram works. Source: own source.

A diagram is a graphic in which information about a process or system is simplified and schematized. It can be simple or complex, with few or many elements. It is a complete summary, which serves to know and interpret information in a simple and visual way [47].

The main advantages of using the affinity diagram are [47]:

- Organizes many ideas and concepts, very useful when you have a large volume of information without order.
- Allows you to understand a situation or problem in more depth
- It manages to focus the efforts of the work group, which allows you to work as a team.
- It is a visual method, which induces group creativity.
- Facilitates subsequent analysis
- It is used in many fields, and being one of the 7 new quality tools, of course you can use it in quality control issues.

The method is mainly used when information needs to be sorted and grouped; but what if there is not so much information that needs to be sorted. It is advisable to use it when there are more than 12 elements, otherwise analyzing the ideas separately is more than enough [147].

The steps to be developed are the following (Figure 7.4) [47]:

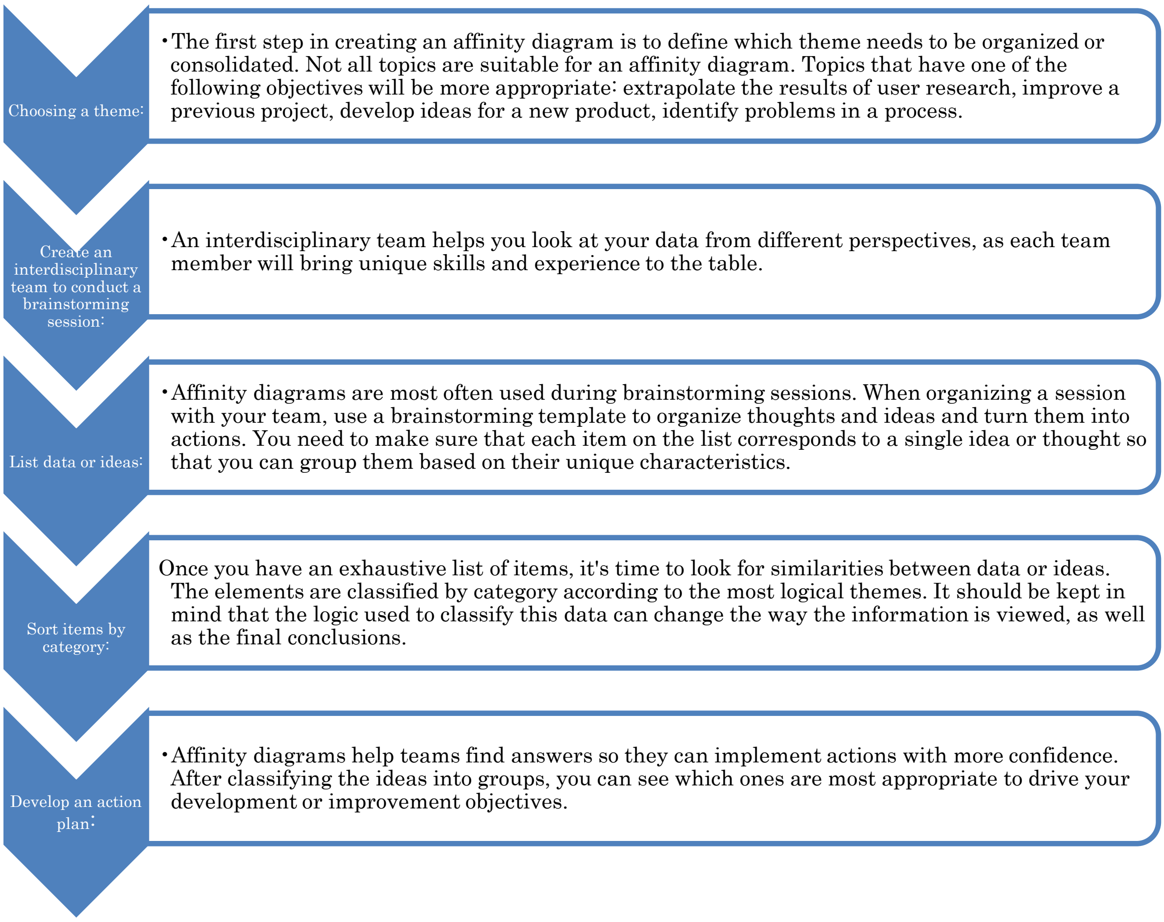


Figure 7.4: Steps of affinity diagram. Source: own source.

The selection of experts in the field of application for the generation of the affinity diagram is based on the need to cover a diversity of perspectives and experiences, thus ensuring a comprehensive representation of knowledge in the area. This extensive group of experts seeks to reduce individual biases, validate findings, and deepen the exploration of ideas, enriching the diagram with a variety of voices and insights. Meaningful expert involvement not only enhances the credibility of the study, but also makes it easier to identify key relationships and gain consensus around the importance of relevant factors in the field of application.

In the selection of experts for the generation of the affinity diagram, rigorous criteria were applied based on professional experience, thematic specialization, diverse representation, previous achievements and contributions, collaborative skills, interdisciplinarity, availability and commitment, as well as recognition in the scientific community. These criteria ensure an equitable and meaningful participation of experts with diverse perspectives and expertise in the field, thereby strengthening the validity and breadth of the analysis in the study.

The dynamic of conducting two different expert panels in the research study has been an effective strategy to address different aspects of the research and enrich the quality of your results. The dynamics and justification for choosing two different panels are explained below, as well as the advantages of having carried out these dynamics:

Dynamics of the Expert Panels:

Panel 1 - Affinity Diagram in Metaverse in Spanish Ports (Participants from the Academic World, 15 People):

- Selection of Experts: A group of experts was chosen, mainly from the academic field, which ensured a solid and theoretical knowledge base on the subject of the metaverse in Spanish ports.
- Brainstorming strategy: Experts participated in brainstorming sessions to generate a wide range of ideas and concepts related to the metaverse and its application in ports.
- Creation of the Affinity Diagram: From the ideas generated, an affinity diagram was created that helped organize and structure the ideas and concepts.

Panel 2 - Weighting of Blocks and Subblocks (Participants from the World of Consulting, Port Actors and Academics, 10 Experts):

- Selection of Diversified Experts: A diverse group of experts was chosen, including consulting professionals, port actors, and academics. This diversity ensured a variety of perspectives and experiences.
- Evaluation of Blocks and Subblocks: Experts evaluated and assigned weights to the blocks and subblocks of the affinity diagram created in Panel 1. This assessment was based on the relevance and priority of each block and sub-block in relation to the metaverse in Spanish ports.
- Reaching Consensus: Experts participated in online discussions and negotiations until reaching consensus elements in the allocation of weights.

7.4. Results

The working group was formed by 22 people related to the Spanish port area, a leader and two coordinators were appointed. The working session took place over the course of a morning in which the members of the team met in person.

An element to take into account when designing an affinity diagram is that the working group must be made up of trained personnel in the subject on which it is discussed, because only in this way is it guaranteed that the conclusions drawn from the process are really useful and accurate. That is why the creation and selection of the group of experts was much discussed.

The experts knowledgeable about the subject of work included in post-it the key elments to have the account for the metaports and later with the help of the leaders and coordinators these indicators were exposed and by consensus they were grouped into different groups.

7.4.1. Category 1: Data

Data collection: DR

RD1-Real-time data

Obtaining data (entry/exit of goods/ships...) in real time between the sections of the port, the status of the goods and the rest of the country's ports. Getting and storing data is the first step in turning a port into a "metaport."

RD2-Exchange of information in the transport chain

A fundamental aspect for the development of a port is its connectivity and accessibility from the land side from the point of view of the exchange of information in the transport chain: it is essential that port infrastructure is integrated with land transport through effective systems and means.

RD3-Open-data

The creation of an open and updated database, searchable by universities and companies in the sector and local, which serves as a meeting point for the public and private sector forming alliances that allow the development of applications and innovative ideas for the digitalization of the port.

RD4. Cloud computing

For the correct and effective functioning of all the operations that take place in a port it is necessary to know, manage and be able to analyze the data quickly and safely.

7.4.2. Category 2: New operating models

Interface:IN

IN1-Loading-unloading systems modernization

Modernization of ship unloading systems to obtain a combination of technology and human labor, just as on Indonesian farms where stevedores can remotely perform their work.

IN2-Port Status Monitoring: Real-time port conditions

Through images, cameras or some kind of sensor it is possible to constantly monitor the status of a port in all its aspects. This allows faster intervention in case of breakdown or malfunction.

IN3-Autonomous vehicles by remote control

Self-driving vehicles use artificial intelligence to function. In a "metaport" they are necessary to integrate the digitized system to the vehicles that transport goods within the port and the different areas.

IN4- Digital planning and management instruments

Ports must use digital instruments for planning and management, and integrate all data inside. With the idea of digitizing all the information and reaching a "metaport", it is important to start using new technologies and integrate the port data for later use.

IN5-Programmed comodality

Both the shipping company and the sender or receiver of the cargo will have an identified access in a virtual platform of the port itself, which allows them to calculate and contract the optimal transport chain.

IN6-Metaformation

Creation of a model of the port in the metaverse in which professionals can practice tasks such as towing ships on arrival and departure from port, loading and unloading by cranes carried out by stevedores or even tasks such as the detection of prohibited goods (drugs, weapons, etc ...) and situations of terrorism for the security forces of the port.

IN7-Traceability of goods (GIS)

It consists of, through geographic information systems, tracking goods or ro-ro cargo in terminals.

IN8-Real-time docking/undocking

Develop real-time ship monitoring systems that allow knowing their situation both to estimate the hours of arrival at port, and to estimate the time of departure once the loading and unloading or embarkation and disembarkation operations have been completed. This would improve operations and quality of service.

Automation: AU

AU1-Identification of vessels through smart technology

Detection and identification of ships by serial numbers/codes through intelligent technology for better management and organization prior to arrival at port.

AU2-Artificial Intelligence Software

They need to practice and develop software to reach a very effective artificial intelligence A "metaport" works with artificial intelligence.

AU3- Blockchain System

The use of blockchain technology is indispensable for a port that aims to be fully digitized.

AU4-Robotization

Implementation of autonomous robots in different processes of the supply chain.

AU5-Self-guided equipment

Implementation of self-guided equipment, such as drones, that help the physical security of the port through its continuous processing of information through real-time inspection of the port and send this information to security systems and equipment.

AU6-Simulation

Development of simulation systems within the supply chain.

Cybersecurity: CB

CB1-Data Security

All digitized data must be secure, there will be data that can be public, such as the occupation of the port in real time, and others that only the client can know, such as the status of their cargo, how and when it will be transported etc.

CB2-Physical infrastructure at the service of data collection

Technologically advanced cameras must constantly monitor all places in the port and keep track of the recordings made, allowing total remote control through apps or software.

CB3- Security Protocol Management

Ensure the implementation of effective security protocols that address cyber threats and ensure the protection of critical data and systems in ports.

CB4- Security Training & Awareness

Train port staff in cybersecurity practices and threat awareness. Ensure that all actors in the port are well-informed and prepared to address potential vulnerabilities and security risks.

CB5- Cyber Incident Management

Develop an incident response plan to identify, contain and mitigate cyber incidents in the port environment. This includes the formation of response teams and the documentation of procedures.

CB6- Technical Support & Quick Resolution

Establish an efficient technical support system to address technical problems and ensure a quick resolution of incidents that may arise in the daily operations of the port. This involves the availability of trained personnel and incident tracking systems.

7.4.3. Category 3: Customers and services

Customer Relationship: CR

CR1-Information connections "post-port"

Implement the system of collection and exploitation of the transport data "post-port" of the different goods that arrive at the port in a real way, including any unforeseen event or change that must be included in these data.

CR2-Meetings in virtual reality

Through the use of virtual reality viewers, create virtual meetings that simulate the physical presence of those present in the same room or in the same collaborative environment, achieving a correct interaction between the subjects.

CR3-Process simulators in virtual reality

Simulate, test and teach the client activities without having to do them. Through the use of virtual and augmented reality, it is possible to simulate and let customers try activities so that they can buy them having had the best possible prediction of reality.

CR4-Decision Support

Provide services and tools that help port customers make informed and strategic decisions. This involves offering advice, data analytics, and resources that enable customers to optimize their operations and transportation routes efficiently and cost-effectively.

Quality of Service: SC

SC1-Data interconnection

Improvement of the internal data connections of the port, everything must be interconnected with the data processed and shared with the personnel / client that concerns you.

SC2-Need to compare with other ports to remain competitive.

In order for port planning to be more efficient and more in line with the latest technological and technical developments, the port management mode must be compared with others, in order to remain competitive.

SC3-Propose new challenges in the supply chain.

The supply chain of a port faces many challenges, such as cost control, customer service, supplier management... To become a "metaport", new challenges are needed to improve and remain competitive.

SC4-Interactivity and interoperability

To become a digitized and modern port, it is essential that data exchange is fast and efficient.

SC 5-Cost reduction and increased productivity

By replacing older machinery and technologies with more modern, technologically advanced, efficient and sustainable ones, it is possible to reduce costs and time throughout the port system and, at the same time, increase productivity.

SC 6-Virtual reality training courses

Training courses within virtual reality allow more people to participate, increasing the level of overall training of employees. They also significantly improve the experience and create a more favorable learning climate.

SC 7-Pollution reduction and sustainable solutions

Pollution is an important issue today and will be even more so tomorrow. The data used by new technologies should help us reduce our pollution and find more sustainable solutions to the "metaport".

SC 8-Optimization of sectors involved

In a port there are different sectors. The demands of each sector that develops the port are different. It is essential to have a personalized approach for each sector and, therefore, customize its management in the metaverse.

SC9- Operational Efficiency Assessment

Implement an operational efficiency measurement system that allows the evaluation and optimization of processes in the port.

Port Management: PM

PM1-Monitoring of all processes

Monitoring of all the processes carried out by the port, in order to find those processes with less efficiency or that are a bottleneck within other more complex processes, either to make small adjustments to the process, or to increase the number of process workers or to find new ways to carry out that process.

PM2-Energy management

Monitoring electricity, fuel, water and gas supply activities would optimize the consumption of these resources. Through this monitoring, processes could be integrated and automated to reduce costs.

PM3-Waste management

The volume of waste from ships could be quantified through sensors that model the solid generated. With this system, it would be possible to dispense with the agents in charge of reviewing the production of this waste, and reduce the costs derived from these inspections.

PM4- Virtual customs inspections

Virtual customs inspections at any port. In this way, customs inspectors would not have to go in person to inspect the merchandise, but could do so virtually in the metaverse.

PM5- Innovation and Technological Development

Promote innovation and technological development in the port to improve efficiency and competitiveness.

PM6- Circular Economy Management

Promote circular economy practices in the port, reducing waste and promoting the reuse and recycling of resources

PM7- Optimization of Port Operations

Constantly seek to optimize the port's operations, from the reception of goods to loading onto ships.

7.4.4. Category 4: Cooperation and institutional coordination: CC

CC1-Incubators and start-ups

Creation of an incubator for the development of integrated solutions with the port authority, the maritime industry could make funds available to finance start-ups whose vocation is to provide them with new digital tools.

CC2- Internal Entities of Metaverse Deployment

In many companies in these sectors, internal entities have been created to deploy digitalization.

CC3-Public-Private Collaboration and Involvement

Encourage collaboration and active involvement of both the public and private sectors in the implementation of port improvements.

CC4-Public institutions with control and supervisory functions

The State and the different municipalities must have a kind of control and supervision function.

CC5- "Goal" spaces

More office spaces are needed so that the "goal" part can be developed. For this it is necessary that Internet connections work, as well as 5G.

CC6- Decision Making Support

Provide resources and advice to assist stakeholders in making strategic decisions related to port modernization.

7.4.5. Category 5: Technological Maturity and Sectoral Assimilation

TM1- Technological Maturity

It comprises the degree of adoption of metaverse technologies in the port sector and the existence of metaverse-related product standards.

TM2- Assimilation Capacity of the Sector

It should take into account the level of education and skilling of port staff in metaverse technologies, as well as the degree of acceptance and participation of port companies in metaverse projects.

TM3- Technological Homogenization

On this point, the degree of compatibility between the different technological tools used by Spanish ports will be fundamental, as well as the level of interoperability between systems and platforms related to the metaverse.

TM4 - Diversity of Port Tools

As is the case in the Spanish port sector, it will be necessary to determine the number of specific tools used by different ports, in order to establish the degree of complexity in the management of multiple technological systems in the same port, so that an evaluation of the efficiency and effectiveness of the existing tools can be carried out.

TM5-Acceptance and Fear of Change

It would be necessary to know in advance the willingness of the actors in the port sector to adopt metaverse technologies, as well as to identify the barriers and concerns related to the assimilation of these technologies, for this communication and awareness strategies in the sector must be evaluated.

In the Figure 7.5 it can be seen the affinity diagram.

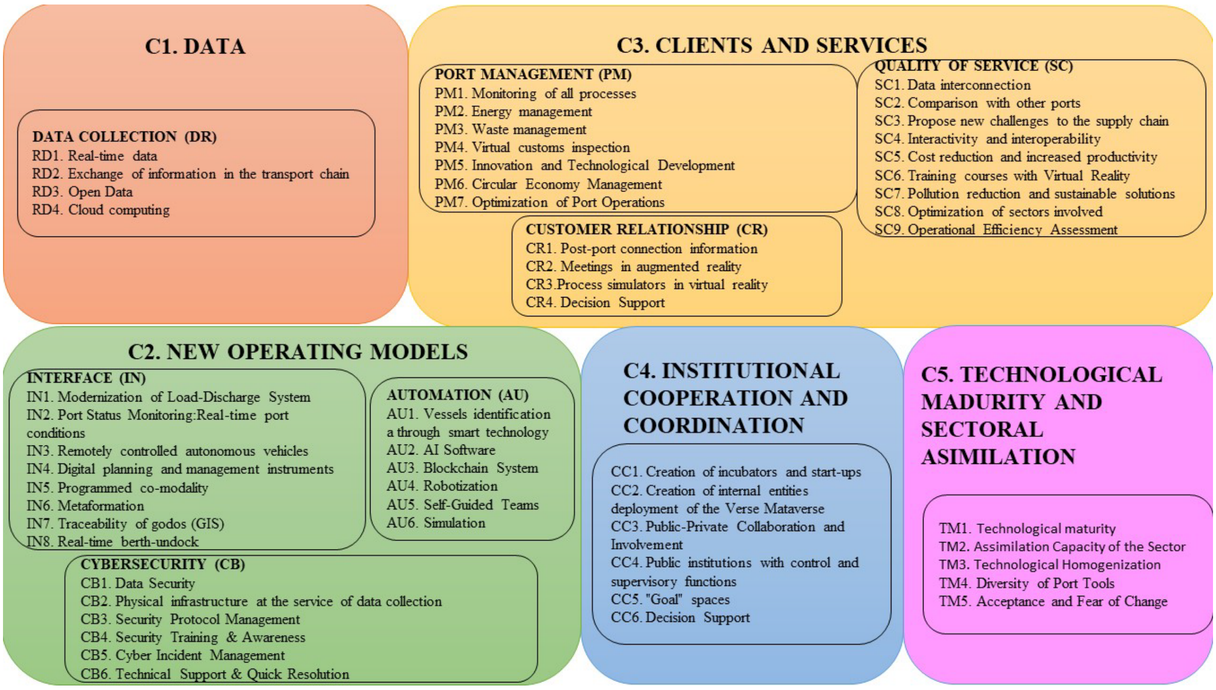


Figure 7.5: Affinity diagram. Source: own source.

With the second panel of experts, the following elements were obtained (Table 7.1):

Table 7.1: Weights in the Affinity Diagram. Source: own source.

CATEGORY	CATEGORY WEIGHT	SUBCATEGORY	SUBCATEGOY WEIGHT	KEY ELEMENT
C1- DATA	30%	DR-DATA COLLECTION	100%	RD3- Open data
C2- NEW OPERATING MODELS	10%	IN- INTERFACE	30%	IN4- Digital planning and management instrument
		AU- AUTOMATION	20%	AU2- AI software
		CB- CYBERSECURITY	50%	CB1- Daa security
C3- CLIENTS AND SERVICES	15%	PM- PORT MANAGEMENT	60%	PM7- Decision support
		SC- QUALITY OF SERVICE	25%	SC9- Operational efficiency assessment
		CR- CUSTOMER RELATIONSHIP	15%	CR4-Decision support
C4- INSTITUTIONAL COOPERATION AND COORDINATION	10%			CC3- PPP and involvement
C5- TECHNOLOGICAL MADURITY AND SECTORAL ASIMILATION	35%			TM1- Technological madurity
				TM2- Assimilation capacity of the sector

The dynamic of using two different expert panels in the research study was an effective strategy to address different aspects of the topic, enrich the content, and ensure validation of the results through expert consensus.

7.5. Analysis of results

This study focuses on the evaluation of the implementation of the metaverse in the port context, highlighting two main categories that have proven to be of great relevance in this analysis: Category 1 (Data) and Category 5 (Technological Maturity and Sector Assimilation).

Category 1, which accounts for 30% of the weight in our research, focuses on the importance of data collection and management in ports. The research has revealed that obtaining real-time data, interoperability of information systems in the transport chain, and the creation of open databases are essential pillars in the transformation of ports into true 'metaports'. These findings underscore the need to establish efficient data collection and management systems to drive digitalization and automation in the port sector.

On the other hand, Category 5, which accounts for 35% in this analysis, focuses on the technological maturity and assimilation capacity of the port sector in relation to the metaverse. The study has identified the importance of staff training, the acceptance of port companies in metaverse projects, technological homogenization and the evaluation of the diversity of tools used. In addition, it is crucial to understand the willingness of industry players to adopt these technologies and address the barriers and concerns related to their uptake. These results emphasize the need to develop specific strategies to foster the adoption of the metaverse in the port sector.

Taken together, the research findings underscore the importance of Category C1 in the fundamental foundation of transforming ports into 'metaports' through data management, while Category 5 plays a crucial role in assessing the sector's technological maturity and ability to successfully adopt and integrate metaverse technologies. These findings are essential to inform future implementation and development strategies in the port space in the metaverse era.

If Category 2 (New operating models) has a weight of 10% in the analysis of your study for the transformation of Spanish ports into "metaports," this means that in the context of the study, the considerations related to the new operating models contribute 10% to the overall assessment of the feasibility and effectiveness of this transformation.

This focus on institutional cooperation and coordination underscores the importance of involving multiple actors and stakeholders in the transformation process. Although this category has a weight of 10%, its impact on collaboration and ensuring that the interests of both the public and private sectors are considered on the path to digitalisation and the creation of 'metaports' cannot be underestimated. It is essential to remember that, although each category has its own weight in the analysis, the synergy between all categories is essential for an effective and complete transformation of Spanish ports towards the desired future of 'metaports'."

According to the results of the panel of experts, the emphasis and priority in the transformation of ports into "metaports" lies in the creation of an open and updated database, accessible to universities and companies in the sector. This has several implications for the analysis of results:

Emphasis on Open Data: The analysis should highlight that the panel of experts prioritizes open data in the transformation process. This suggests that they consider it critical for ports to provide open data that is accessible to various actors, which can foster innovation and collaboration in the sector.

Collaboration and Partnerships: The emphasis in RD3 indicates the importance of fostering collaboration between universities, companies and other stakeholders in the port area. This may involve the formation of alliances for the development of innovative applications and solutions in the context of port digitalisation.

Data Unification and Automation: Creating an open and up-to-date database is key to data unification and automation in ports. This can lead to greater efficiency and consistency in information management across ports, which is essential on the road to "metaports."

Communication of Results: In the analysis of results, it should be highlighted how the priority given to RD3 influences the strategies and approaches recommended for port transformation. It is important to communicate how this emphasis on open data can contribute to the digitization and modernization of ports and the achievement of "metaport" goals.

According to the expert panel, the most driving elements in Category 2 (New operating models) are IN4 (Digital planning and management instruments), AU2 (Artificial Intelligence Software) and CB1 (Data Security), each within its subcategory, this means that these elements play a prominent role in the transformation of ports into "metaports" from the perspectives of digital planning and management, Artificial intelligence and data security.

The IN4 element, which focuses on the adoption of digital tools for the planning and management of port operations, represents a cornerstone in the transformation towards "metaports." The digitalization of planning and management processes is essential to improve efficiency and coordination in ports. By adopting digital technologies and tools, Spanish ports can optimize resource management, schedule operations, and improve decision-making. Digital planning and management allow for greater synchronization of operations, which is crucial for operational efficiency and cost reduction.

AU2 highlights the importance of developing artificial intelligence software to drive port transformation. Artificial intelligence plays a critical role in automating and optimizing port operations. Implementing AI algorithms can improve efficiency in resource allocation, demand forecasting, and decision-making based on real-time data. In addition, AI can contribute to the early detection of problems and the continuous improvement of port processes. This is essential for the transformation of ports into highly efficient and technologically advanced "metaports".

CB1, which focuses on data security, is a critical component of the transformation to "metaports." In a digitalized environment, the protection of sensitive data is essential. Ensuring the confidentiality, integrity, and availability of data is critical to the safe operation of ports. Implementing effective security measures, such as encryption, authentication, and constant monitoring, is crucial to prevent security breaches and protect critical information. Data security is a pillar for customer trust and the long-term sustainability of "metaports."

These driving elements in Category 2 indicate that digitalization, artificial intelligence and data security are critical to driving the transformation of Spanish ports into highly efficient, technologically advanced and secure "metaports". The combination of advanced technology and robust security measures will enable ports to adapt to changing demands and achieve greater efficiency in their operations.

For category 3, according to the panel of experts, the identification of the most important elements to boost Spanish "metaports" in the short term such as PM7 (Optimization of Port Operations), CR4 (Decision Making Support) and SC9 (Evaluation of Operational Efficiency) has important implications for the future of Spanish ports. Below, we'll take a look at what this means for Spanish ports:

The priority given to the optimisation of port operations (PM7) points to the importance of improving efficiency at all stages of port operations, from the reception of goods to loading onto ships. For Spanish ports, this implies:

Increased Efficiency: Optimizing processes and implementing advanced supply chain management systems will enable greater efficiency in port operations. This will result in reduced costs, increased productivity, and faster turnaround times.

Competitiveness: Spanish "metaports" will be more competitive internationally by offering more efficient and profitable operations. This will attract more businesses and cargo, which will boost economic growth.

Advanced Technology: The adoption of advanced technologies, such as automation, real-time tracking and artificial intelligence, will play a fundamental role in optimizing port operations.

The importance of supporting port customers in decision-making (CR4) involves a focus on collaboration and the provision of services that help customers optimize their operations. This means:

Client-Port Relationship: Spanish "metaports" will be more focused on building strong relationships with their customers. This will include advice, data analysis, and resources that enable clients to make informed, strategic decisions.

Supply Chain Efficiency: Ports will become strategic partners for their customers, providing services that enable more efficient supply chain management. Informed decision-making will improve customers' competitiveness.

Customized Services: Spanish ports will offer customized services and tailor-made solutions to meet the specific needs of customers. This will foster customer loyalty and business growth.

The implementation of an operational efficiency measurement system (SC9) highlights the importance of constantly evaluating and optimizing processes in the port. This involves:

Continuous Improvement: Spanish "metaports" will be committed to a culture of continuous improvement. Constant evaluation will allow you to identify areas for improvement and take corrective action.

Operational Efficiency: Operational efficiency is essential to better serve customers. Measuring and optimizing efficiency will ensure that operations are conducted as efficiently as possible.

Customer Experience: Evaluating operational efficiency not only benefits the port but also customers. More efficient operations improve the customer experience and strengthen business relationships.

The prioritisation of PM7, CR4 and SC9 means that Spanish "metaports" will focus on process optimisation, efficiency improvement, informed decision-making, collaboration with customers and constant evaluation of operations. This will contribute to a more competitive, technologically advanced and customer-oriented port, driving growth and excellence in the Spanish port sector.

The identification of CC3 (Public-Private Collaboration and Involvement) as the most important element to promote the transformation of Spanish ports into "metaports" within Category 4 (Cooperation and institutional coordination) has a solid and significant justification, CC3 (Public-Private Collaboration and Involvement) is fundamental for the promotion of Spanish ports towards "metaports" due to its capacity to foster strategic collaboration, shared finance, innovation and sustainable development. Public-private collaboration makes it possible to face the challenges and take advantage of the opportunities in port modernization, promoting faster and more sustainable growth in the Spanish port sector.

The identification of both TM1 (Technological Maturity) and TM2 (Sector Assimilation Capacity) as drivers to turn Spanish ports into "metaports" is of great relevance. This is because these elements play a critical role in modernizing ports and adapting them to a digital and metaverse environment.

TM1 (Technology Maturity) points out the importance of being at the forefront of the adoption of digital and metaverse technologies. This implies that Spanish ports must embrace advanced technologies, such as virtual reality, artificial intelligence, and automation, to improve their efficiency, safety, and sustainability. In addition, the existence of standards and protocols in the sector is essential to ensure interoperability and system integration. Investing in research and development of metaverse technologies is a crucial element of staying competitive in an ever-evolving environment.

TM2 (Sector Assimilation Capacity) highlights the need for port staff to be trained and prepared to adopt and leverage these technologies effectively. Education and training are essential to ensure that staff can adapt to new technologies. Collaboration with other industries, such as aeronautics, can provide valuable knowledge and experience in adopting digital technologies. In addition, the existence of policies and programs to encourage the adoption of the metaverse in the sector is a crucial factor in driving technological modernization.

The combination of Technological Maturity (TM1) and Sector Assimilation Capacity (TM2) indicates that Spanish ports are committed to the adoption of advanced technologies and the training of their staff to assimilate these technologies effectively. This strategy is essential to deliver more efficient, safe, and sustainable operations, improve competitiveness, and provide high-quality service to its customers. The successful transformation of ports into "metaports" depends to a large extent on the combination of technological maturity and assimilation capacity of the sector.

For the case study:

Determining the percentage of progress of Port1 towards "metaport" status would require a detailed and specific assessment based on several factors, including the implementation of technologies, training of personnel, collaboration with other industries, and the adoption of sustainable practices.

An overall assessment can be provided based on the information obtained:

Category 1: Data (3/10 of 30%): The Port of Algeciras has made significant progress in the collection, management and use of real-time data (RD1), exchange of information in the transport chain (RD2), creation of an open database (RD3) and the implementation of cloud technologies (RD4), could have a significant percentage in this category.

Category 2: New Operating Models (3.5/10 of 10%): Port1 would have to demonstrate a high degree of modernization in loading and unloading systems (IN1), real-time control of port conditions (IN2), adoption of autonomous vehicles (IN3), use of digital tools for planning and management (IN4), as well as the implementation of scheduled modalities (IN5). The adoption of these advanced operating models would contribute significantly to this percentage.

Category 3: Customers and Services: For this category, the implementation of virtual reality technologies, such as virtual meetings (CR2), virtual reality simulators (CR3), and decision support (CR4) would be required to meet customer needs and improve service quality. In addition, improving quality of service (SC1) and data interconnection (SC2) are also critical factors.

Category 4: Cooperation and Institutional Coordination (8/10 of 15%): Cooperation and collaboration with other actors in the sector and the creation of incubators and startups (CC1) are essential. Port1 must demonstrate its ability to promote these initiatives.

Category 5: Technological Maturity and Sectoral Assimilation (2.5/10 of /35%): Technological maturity (TM1) and industry assimilation capacity (TM2) are critical. The port must be at the forefront of adopting metaverse technologies and be able to assimilate these technologies effectively.

Transformation to a "metaport" is an ongoing process that can take significant time and resources to fully achieve.

7.6. Conclusion

Virtual reality, artificial intelligence, interactivity, blockchain, IoT, digital twin... The metaverse of logistics, the next revolution born of the internet, poses new challenges for supply chains and of course for the future of ports. The metaverse represents a leap in internet connectivity, supported by 5G and characterized by interactivity, simulation, a decentralized environment, and a virtual reality that, although not physical, is persistent and directly linked to the real world. The metaverse is a step further, since it is not only able to faithfully reproduce what happens in a certain space, but also recreates a parallel universe with which we can interact. In this parallel reality we can propose or simulate alternative scenarios for different purposes.

The blocks with the highest number of indicators correspond to new operating models and to customers and services, it is in these blocks where the greatest efforts will have to be made.

Within the operating models is automation, the metaverse could allow the implementation of autonomous systems for the transport and loading of goods, as well as for the maintenance and repair of port equipment. These systems could be remotely controlled and monitored in real time across the metaverse, reducing the need for human intervention and minimizing the risks associated with workplace accidents.

Regarding cybersecurity, security is a critical aspect in the operation of ports. In the metaverse, risk scenarios could be simulated and security measures tested to assess their effectiveness before implementing them in real life. In addition, the metaverse could be used to monitor and detect potential security threats in real time, allowing for a quick and effective response to emergency situations.

In the customer and services block is the service quality sub-block, in terms of quality of service, the metaverse can be used to simulate different situations in which the port is used, including the handling of dangerous cargoes, the safety of people and equipment, and the efficiency of the loading and unloading process. By simulating these scenarios, potential problems and areas for improvement can be identified, which can help improve the quality of service at the port.

Overall, the use of the metaverse in ports and quality of service can provide a valuable tool to improve port efficiency, security, and profitability. However, it is important to note that the implementation of this technology is still under development and may require significant investment in terms of hardware, software, and staff training.

Supplementary Materials: The following supporting information can be downloaded at: www.mdpi.com/xxx/s1, Figure S1: title; Table S1: title; Video S1: title.

Author Contributions: this article has been developed as a team work, in which all authors have contributed in the different task to be done: Conceptualization, methodology, validation, formal analysis, investigation, resources, data curation, writing, review and editing, visualization and supervision. All authors have read and agreed to the published version of the manuscript.

Based on the identification of driving elements for the transformation of Spanish ports into "metaports" by the panel of experts, several key conclusions can be drawn:

Technology and Digital Transformation: Technology and digital transformation are fundamental elements for the modernisation of Spanish ports. The adoption of advanced technologies, such as virtual reality, artificial intelligence, and automation, plays a crucial role in improving operational efficiency, safety, and sustainability.

Interoperability and Standards: The existence of standards and protocols in the sector is essential to ensure interoperability and system integration. This facilitates collaboration between different actors in the port and allows for the transfer of data and knowledge more effectively.

Education and Training: Training port staff in metaverse technologies is essential for the successful assimilation of these technologies. Adaptability and the ability to learn how to use these technologies are critical.

Cross-Sector Collaboration: Collaboration with other industries, such as aeronautics, can provide knowledge and expertise in adopting digital technologies. Collaboration and information sharing are key factors for success in port modernization.

Promotion Policies: The existence of policies and programs to promote the adoption of the metaverse in the sector is essential. These programs may include incentives and financial support for technological modernization.

Efficiency, Competitiveness and Sustainability: The modernization of ports not only seeks to improve efficiency and competitiveness, but also sustainability. Cost reduction, process optimization, and resource management are key elements in this transformation.

The transformation of Spanish ports into "metaports" involves significant investment in technology and training, as well as close collaboration between actors in the port sector and other related industries. Technological modernisation and the adoption of sustainable practices are key elements for the future of Spanish ports and their ability to compete internationally in an increasingly digital environment.

8. CASE STUDY 1: APPLICATION OF THE E.T.S. TO EUROPEAN PORTS

This chapter presents the accepted manuscript of RA4 that has been published in a peer-reviewed and indexed journal:

Vaca-Cabrero, J., González-Cancelas, N., Camarero-Orive, A., Corral, M. M. E.-I., & Ricci, S. (2024). Economic Impact of the Application of the ETS to European Ports: Analysis of Different Scenarios. *Sustainability*, *16*(23), 10433. https://doi.org/10.3390/su162310433

Abstract: The fight against climate change is one of the main global challenges of our time, and the European Union (EU) seeks to achieve climate neutrality and energy transition for the continent by 2050 through different policies. This research studies the economic implications of the EU Emissions Trading System (ETS) on European ports. By analysing various maritime scenarios, the study assesses how the ETS influences shipping routes, port competitiveness and overall economic activity. A key finding is that the ETS imposes significant additional costs on shipping companies, which could lead to adjustments in routes and a shift in cargo volumes to ports in regions with less stringent environmental regulations. This could result in job losses in European port communities and reduce the competitiveness of European ports. In addition, the potential for carbon leakage, where shipping activities are simply relocated to regions with fewer emission controls, is explored.

Keywords: ETS, Competitiveness, Green Ports, European Ports, Route Analysis, Emissions, Sustainability.

8.1. 1. Introduction

The fight against climate change is one of the major global challenges of our time, and the European Union (EU) has been a pioneer in implementing policies to mitigate greenhouse gas emissions [26]. Taking a firm stance on reducing emissions, not only as an environmental commitment, but also as an opportunity to lead the transition to a more sustainable and resilient economy.

With the aim of achieving climate neutrality by 2050, the EU launched the European Green Deal, an ambitious strategy covering various sectors of the economy, from energy and transport to agriculture and industry. This roadmap not only aims to reduce greenhouse gas emissions, but also to transform the European economy, making it more resource-efficient and less dependent on fossil fuels [32]. In this sense, it also seeks to encourage technological innovation and the creation of new green jobs.

One of the key pillars of the Green Deal is the Fit for 55 legislative package, presented in 2021. This package, which covers multiple regulatory areas, has as its main objective to reduce greenhouse gas emissions by at least 55% by 2030, taking 1990 levels as a reference [148]. To achieve this goal, a number of measures have been proposed that affect different sectors, including maritime transport, as well as energy production and the use of natural resources.

Within the framework of the Blue Economy, which is all those economic sectors related to the ocean [7], one of the most notable developments is the inclusion of maritime transport in the EU Emissions Trading System (EU ETS). Until recently, shipping, responsible for about 3% of global greenhouse gas emissions, was not subject to the same strict regulations as other industrial sectors. However, with the expansion of the EU ETS, the maritime sector will now be forced to reduce its carbon emissions, a crucial step towards achieving the EU's climate goals. This system requires shipping companies to purchase permits for every ton of CO2 they emit, creating a financial incentive to reduce their carbon footprint and adopt cleaner technologies [149].

The inclusion of maritime transport in the EU ETS poses a number of important challenges for the European shipping industry and ports. In terms of competitiveness, EU ports could face increased costs, as shipping companies will have to pay for their emissions, which could lead some operators to look for ports in third countries that are not subject to these regulations [150]. This could lead to carbon leakage, i.e. the transfer of polluting activities to areas where regulations are less stringent [151]. On the other hand, ports and shipping companies will have to adapt quickly to new environmental regulations, which means investments in cleaner technologies, such as alternative fuels (hydrogen or ammonia) or improvements in the energy efficiency of ships [150].

The main objective of this research work is to analyse the economic impacts of the implementation of the EU ETS on EU ports, with special emphasis on the implications that this may have on the restructuring of trade routes and on the competitiveness of European ports vis-à-vis their counterparts outside the European Economic Area.

To meet this objective, a methodology structured in several phases will be used. First, an Ishikawa diagram will be carried out [152], also known as a cause-effect diagram, to identify and categorise factors that may influence the success or failure of the implementation of the EU ETS in shipping. This analysis will allow the problems to be broken down into key categories, such as technological, economic, regulatory and social factors, to have a comprehensive view of the challenges faced by the actors involved.

Second, simulations of different maritime scenarios will be carried out to predict how shipping companies and ports might react to the new regulations. These simulations will consider variables such as the cost of emission allowances and the competitiveness of ports. Through these models, we will seek to better understand the implications of the expansion of the EU ETS and how different actors could adapt to these changes.

Finally, this work will offer conclusions based on the results obtained, with the aim of mitigating the negative effects of the ETS, protecting the competitiveness of European ports and ensuring that climate objectives are effectively met.

8.2. State of the art

8.2.1. Fit for 55 legislative framework

For some years now, the European Commission has set out to achieve climate neutrality on the continent by 2050 [26]. To this end, the European Green Deal was developed, which is carried out through different packages of measures such as RefuelEU, RepowerEU or Fitfor55.

On 14 July 2021, the European Commission presented the "Fit for 55" package to achieve the targets of reducing greenhouse gas emissions by 2030 by at least 55% compared to 1990 levels [148]. This package proposes a series of 14 measures, of which 4 are closely linked to maritime transport and therefore to port activities:

ETD Maritime: With the new Directive 2003/96/EC on energy taxation, tax exemptions for marine fuels are partially ended. Fuels sold in the European Economic Area (EEA), for travel within the EEA, will no longer be exempt from tax [4]. This directive is still under review in June 2024.

Alternative fuels infrastructure (AFIR): Boosting the expansion of LNG and shore-based power supply facilities in the EU's main ports [153]. The old Alternative Fuels Infrastructure Directive becomes a regulation.

EU Emission Trade System (EU ETS): Maritime transport is incorporated into the Community Emissions Trading System. Ships are responsible for 100% of their CO_2 emissions in and between EU ports, and 50% when entering or leaving the EU. They must pay according to the current carbon market price (€/tonne of CO_2) [149].

Fuel EU: This measure seeks to encourage the adoption of low-emission fuels by imposing limits on the carbon intensity of fuels on board ships. Carbon intensity reduction levels of fuels will progressively increase differently (2% in 2025, -6% in 2030, 75% in 2050) [154].

8.2.2. EU Emission Trade System.

The European Union's Emissions Trading System (EU ETS) is a market-based mechanism designed to reduce greenhouse gas (GHG) emissions in the most CO2-intensive sectors [155] and has been extended to the maritime sector to address rising greenhouse gas emissions from merchant ships. This market mechanism forces shipping companies to acquire emission allowances for each tonne of CO_2 emitted, thus incentivising the adoption of cleaner technologies and fuels [156]. The inclusion of maritime transport in the EU ETS, from 2024, represents a significant step towards the decarbonisation of the sector and the achievement of the EU's climate objectives. The main application features of this system are as follows:

- The Maritime Emissions Trading System (ETS) will apply to all cargo ships and passenger ships over 5,000 GT.
- 100% of the emissions of the intra-European routes, 100% of those made while in port and 50% of the extra-European routes will be covered.
- Gradual application between 2024 and 2026. It will be paid for 40% of emissions in 2024, 70% in 2025 and 100% in 2026.
- Control is extended to methane (CH4) and nitrous oxides (NOx) from 2026
- In 2026, the inclusion of vessels from 400GT will be reviewed. And Offshore Service Vessels of more than 5000 GT will be included from 2027.
- It includes the measure to redefine the "port of call" to avoid carbon leakage, considering "transparent" non-European ports with more than 65% transshipment activity and located less than 300 nautical miles away.
- If the IMO does not implement measures by 2028, an assessment of the impact of the directive will be carried out.

8.2.3. Impacts on the application of emission control regulations.

In recent decades, maritime governance has been undergoing regionalisation that contributes to a more complex and distributed system, where different actors share the responsibility for ensuring the sustainability of maritime transport. Traditionally, the International Maritime Organization (IMO) has been the main regulatory body for global shipping. However, due to growing environmental concerns and the perceived ineffectiveness of IMO in certain areas, regional initiatives have emerged in the European Union [157].

For years, certain maritime areas of the world have been declared Emission Control Areas (ECAs) which have stricter environmental regulations to reduce emissions of sulfur and nitrogen oxides from ships [158]. Some studies indicate that ECAs can have a negative impact on port efficiency. An average efficiency reduction of 15-18% is estimated in ports within the ECAs. This suggests that measures to comply with environmental regulations may lead to additional costs that affect the operational efficiency of ports [159].

On the other hand, ECAs impose stricter restrictions on sulfur and nitrogen oxide emissions, which can affect ship routes and speeds. Mathematical models currently exist to optimize the speed of a ship considering fuel costs, travel time and compliance with emissions regulations [160].

In terms of governance and the decision-making model when implementing emission regulation measures, there are two main types of regulations: a unilateral one, implemented by a single region, and a uniform one, applied to all regions [161]. Considering the competition between shipping companies and ports, as well as operational factors such as inventory costs and the balance between fleet size and sailing speed, the results indicate that unilateral regulation can even increase total emissions, while uniform regulation always reduces them. In addition, both regulations can have asymmetric effects on shipping companies and ports [162].

In addition, although on the one hand there is a large concentration of fleet, since the 5 largest shipping companies own 65% of the container transport [163], this is not the case with ports, in Spain alone there are 46 ports of the State. Competition between ports can affect the effectiveness of emissions regulations. In addition, the type of regulation (unilateral or bilateral) also influences the results. A port subject to strict regulation may lose competitiveness compared to ports in regions with less stringent standards, in addition, different regulations may incentivize or discourage investment in clean technologies [150].

On the other hand, it should be noted that carbon leakage in shipping emission control occurs when efforts to reduce emissions in one region or sector lead to an increase in other areas, undermining global goals as air emissions are not a local phenomenon but a global one [151]. This can happen by shifting trade routes, relocating fleets to countries with laxer regulations, or evading regulations by changing flags to states with fewer restrictions. The consequences include a global increase in emissions, competitive inequality and challenges in the effectiveness of emission reduction policies [164]. To mitigate carbon leakage, robust international coordination that establishes homogeneous regulations and avoids imbalances is crucial. Organizations such as the International Maritime Organization (IMO) are key in the implementation of global standards [165]. In addition, monitoring and verification mechanisms must be improved to ensure compliance with regulations, implement economic incentives for companies that adopt sustainable practices, and encourage research and development of cleaner and more efficient technologies. Addressing carbon leakage in shipping requires a comprehensive approach that combines international cooperation, the implementation of homogeneous regulations, and the promotion of sustainable technologies [1].

Some indicators to detect these carbon leaks could be:

- Evolution of the number of calls of ships under 5,000 GT. This size of ships is exempt during these first years from the ETS levy in EU ports, so a significant increase in the number of calls of this type of ship from other non-European ports could mean a clear carbon leakage [166]. The mother ships would carry out the unloading operation at these transit ports and by means of smaller vessels exempt from the ETS they would transport the goods to European ports.
- Trend in the volume of goods in transit in European ports. If European ports that, due to their geographical position, capacity, maritime connectivity index, etc., currently have a high percentage of goods in transit and begin to lose a volume of goods similar to that gained by their non-European competitors, it would be a clear example of this migration of routes to ports exempt from ETS [167].
- Evolution of the distances that the mother ships travel on the last leg of their journey before the European port. If the distance travelled from the last non-European port is significantly reduced, it could be a clear indicator to detect an unusual previous stopover before the implementation of the ETS in order to pay a lower amount for the journey made [168].
- Investments that are being undertaken in both European and non-European ports in terms of increasing the capacity and efficiency of their terminals. If competing ports are identified as investing to increase their

container transshipment capacity, for example, large amounts of traffic may be diverted to these ports [169].

- As for the Short Sea Shipping lines, study the evolution of the volume of trucks that are transported. By applying the ETS package to ships but not the ETS2 to the road, intra-EU traffic that occurs via SSS pays 100% of the emissions and makes it no longer so profitable for trucks to go by boat[33].

On the purely economic side, the application of the ETS to European ports will have a significant negative economic impact due to the increased costs associated with calling at these ports [170]. Shipping companies will face higher operating expenses for having to acquire emission permits for their vessels, which could result in an increase in port fees and prices for related services [171]. This increased cost may discourage shipping companies from using European ports, opting for alternative routes or ports in regions with less stringent regulations, which in turn could reduce maritime traffic and negatively affect local economies that depend on trade and port activity [169]. In addition, the competitiveness of European ports could be compromised, affecting related industries such as land transport, logistics and warehousing, and potentially leading to job losses in these sectors [172].

8.3. Methodology

The methodology proposed in this research work is framed in the following phases.

The general steps of the methodology are (Figure 8.1):

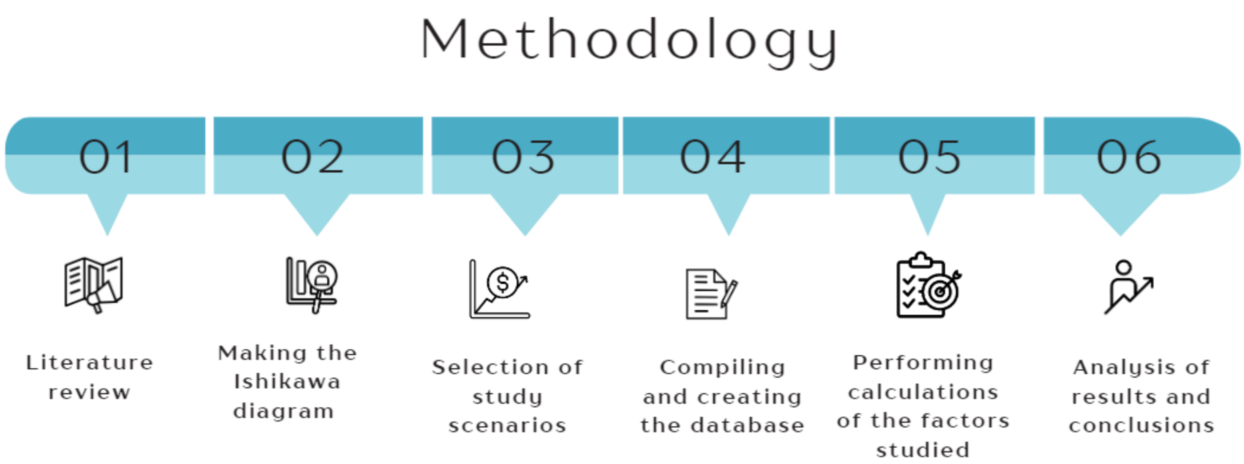


Figure 8.1: workflow. Source: own elaboration.

Phase 1: Bibliographic review. A comprehensive study was conducted to analyze the modes of application of the ETS, its legislative framework, and the expected impacts of its implementation. The literature review covered academic articles, official reports, and EU policy documents. Key sources included the European Green Deal, the Fit for 55 legislative package, and studies on the inclusion of maritime transport in the EU ETS. Databases such as Scopus, Web of Science, and MRV EU repositories were consulted to ensure reliable and relevant data.

Phase 2: An Ishikawa analysis was carried out to detect the main effects of the implementation of the Emissions Trading System (ETS) in the maritime domain. The Ishikawa diagram was applied as a structured tool to identify and classify the effects [152] in order to better understand the critical factors affecting the ports of the European Economic Area due to the implementation of the ETS. Once this was done, the dimension with the most significant effects when applying the ETS was quantified according to a panel of experts from shipping companies, ports, consultancies, and universities.

Phase 3: Selection of study scenarios. Once Ishikawa's analysis was completed, the study focused on analyzing the derived economic aspects in more detail. Different scenarios of maritime routes that could be affected by the application of the ETS on both the Atlantic and Mediterranean coasts were proposed.

Phase 4: Database collection and creation. Once the routes to be studied were selected, data were collected from different sources (MRV emissions, SBC, European Commission, Algeciras Port, among others) and the database was created.

Phase 5: Realization of the factors studied. Once the database was created, the economic effects of a ship's scale were calculated based on the scenarios outlined in Phase 3.

Phase 6: Analysis of results and conclusions. Once the results were obtained, these were analyzed, and the conclusions drawn from the study were compiled.

8.4. Results and analysis of results

The Ishikawa diagram (fishbone) showing the effects of the application of the Emissions Trading System (ETS) to maritime transport in European Union ports, categorized into four main areas: Economic, Social, Governance and Environmental (Figure 8.2).

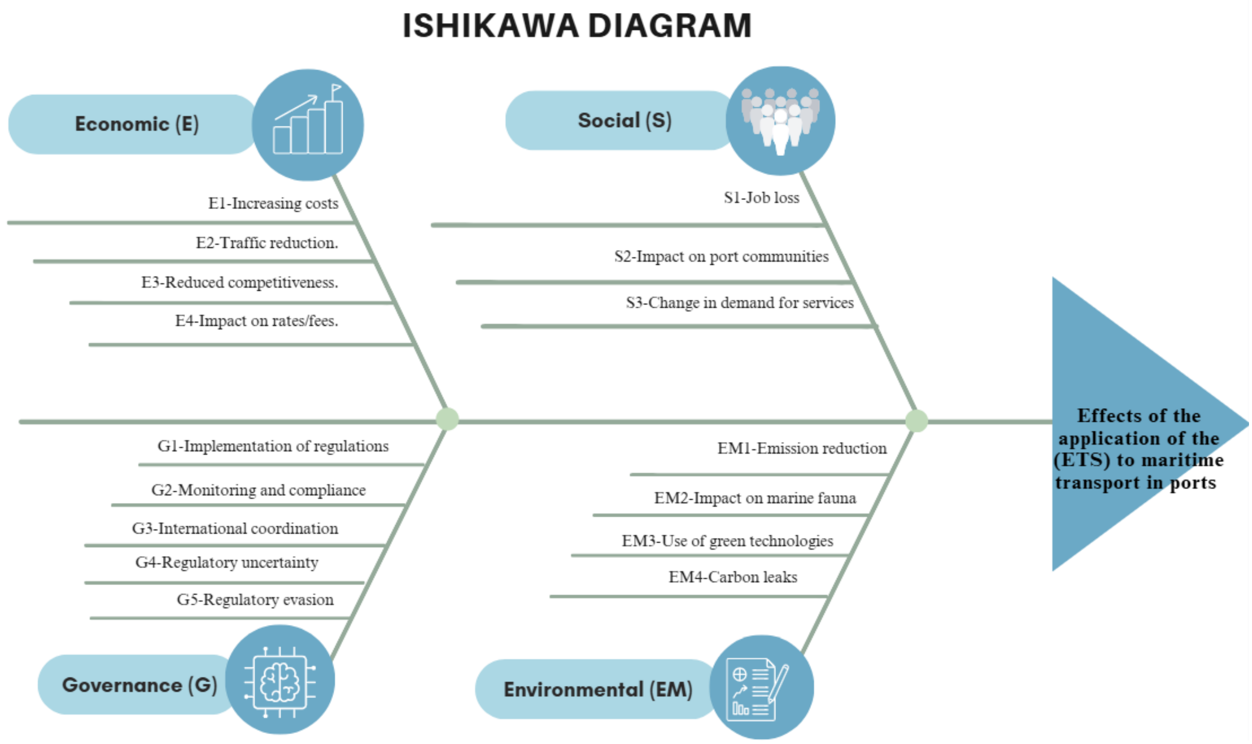


Figure 8.2: Ishikawa diagram. Source: own elaboration

Economy (E):

E1-Increased costs: shipping companies face higher operating expenses by having to acquire emission permits.

E2-Traffic reduction: the increase in costs can dissuade shipping companies from using European ports, reducing the volume of traffic.

E3-Reduced competitiveness: European ports may lose competitiveness to ports in regions with more lax regulations.

E4-Impact on tariffs / fees: the loss of business volume of a port can translate into an increase in port tariffs for users who have been maintained to be able to resist the structure of port expenses.

Social (S):

S1-Loss of jobs: reduced traffic and competitiveness can lead to job losses in the port sector and related areas.

S2-Impact on port communities: Local economies that depend on port trade may suffer due to decreased activity.

S3-Change in the demand for services: the dynamics in the demand for logistics and support services may change, affecting local suppliers.

Governance (G):

G1-Implementation of regulations: the development and application of new regulations is required to control emissions.

G2-Supervision and compliance: it is necessary to establish effective mechanisms to monitor and ensure compliance with regulations.

G3-International coordination: cooperation between countries is crucial to harmonize regulations and avoid competitive inequalities.

G4-Evasion of regulations: companies may attempt to circumvent regulations by changing flags or alternative routes.

G5-Regulatory uncertainty: Shipping companies face uncertainty due to possible changes in policies and regulations.

Environmental (EM):

EM1-Emission reduction: the main objective of the ETS is to reduce greenhouse gas emissions from maritime transport.

EM2-Impact on marine wildlife: the implementation of the ETS can have both positive and negative effects on marine fauna, depending on changes in the routes and technology used.

EM3-Use of green technologies: the need to reduce emissions will encourage the development and adoption of cleaner and more efficient technologies.

EM4-Carbon leakage: Moving operations to regions with less stringent regulations can increase global emissions.

This diagram helps to visualize the different areas of impact and the possible consequences that the implementation of the ETS may have on EU shipping and ports.

Once the Ishikawa diagram was developed, a focus group was conducted with a panel of 8 experts, whose affiliations included: 3 university professors specializing in Port Operations, 1 consultant from a maritime traffic consultancy, 2 representatives from shipping companies, and 2 professionals from the operations department of the public organization Puertos del Estado.

During the session, the experts were asked to rank the four dimensions where the effects of ETS application occur, in order of importance from highest to lowest. This process was carried out in a structured manner, first collecting individual evaluations and subsequently analyzing the combined results. The data obtained were processed to convert them into representative percentages, which allowed the relative impact of each dimension to be quantified.

Based on this analysis, it was concluded that, of the four dimensions considered, the economic dimension has the greatest effect on the development of the competitiveness of European ports (Figure 8.3). Consequently, in the subsequent phases of the study, these economic factors were analyzed in greater detail.

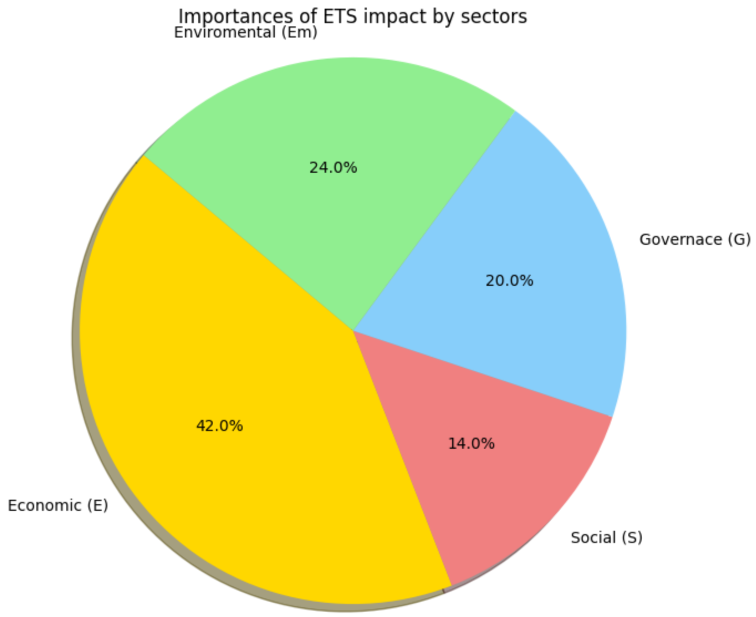


Figure 8.3: impact of ETS application by dimension. Source: own elaboration.

The work scenarios on which the analysis of the study will be carried out are set out below (Table 8.1):

Table 8.1: Scenarios proposed in the study. Source: own elaboration.

Scenario	Scenario Code	Route	Source ports	Intermediate Ports	Destination ports	Circumnavigation of Africa	Non-EEA Intermediate Port is Transparent Port
Scenario 1.1	**E 1.1**	North America-Europe-East	Huston (non-EEA)	Algeciras (EEA)	Dubai (non-EEA)	No	
Scenario 1.2	**E 1.2**		Huston (non-EEA)	Algeciras (EEA)	Dubai (non-EEA)	Yes	
Scenario 1.3	**E 1.3**		Huston (non-EEA)	Tangier (non-EEA)	Dubai (non-EEA)	No	Yes
Scenario 1.4	**E 1.4**		Huston (non-EEA)	Tangier (non-EEA)	Dubai (non-EEA)	Yes	Yes
Scenario 2.1	**E 2.1**		Montreal	Liverpool	Le Havre (EEA)	No	No

			(non-EEA)	(non-EEA)			
Scenario 2.2	**E 2.2**		Montreal (non-EEA)		Le Havre (EEA)	No	
Scenario 2.3	**E 2.3**	North America-Northern Europe	Montreal (non-EEA)	Liverpool (non-EEA)	Le Havre (EEA)	No	Yes
Scenario 2.4	**E 2.4**		Montreal (non-EEA)		Le Havre (EEA)	No	
Scenario 3.1	**E 3.1**		Singapore (non-EEA)	Algeciras (EEA)	Rotterdam (EEA)	No	
Scenario 3.2	**E 3.2**	Asia-Mediterranean-Northern Europe	Singapore (non-EEA)	Algeciras (EEA)	Rotterdam (EEA)	Yes	
Scenario 3.3	**E 3.3**		Singapore (non-EEA)	Tangier (non-EEA)	Rotterdam (EEA)	No	Yes
Scenario 3.4	**E 3.4**		Singapore (non-EEA)	Tangier (non-EEA)	Rotterdam (EEA)	Yes	Yes

- Scenario 1: North America-Europe-East sea route. This maritime route has been chosen because of the importance of connecting the three main continents and the conjunction of areas that produce and consume goods. Some of the legs of this route are: Huston (non-EEA), Algeciras (EEA), Dubai (non-EEA).
- Scenario 2: North America-Northern Europe sea route. The selection of this route aims to demonstrate how to reduce the payment of allowances when interspersing a port in the United Kingdom (non-EEA). The selected example is Montreal (non-EEA), Liverpool (non-EEA), Le Havre (EEA).
- Scenario 3: Asia-Mediterranean-Northern Europe sea route. This last scenario seeks to show the effects of applying ETS in ports where, in the case, as on the EU's southern border, there are third-country ports with the potential to attract this traffic, as this would not apply. The example studied is Singapore (non-EEA), Algeciras (EEA), Rotterdam (EEA) and Singapore (non-EEA), Tangier Med (non-EEA), Rotterdam (EEA).

Finally, it should be noted that in both scenarios 1 and 3, due to geopolitical instabilities in the Bad-al-Mandeb Strait, the calculations made include the casuistry of making the Europe-East route through the Suez Canal or circumnavigating the Cape of Good Hope. A clear example of this is the route of the Maersk Chicago ship that covers the route of scenario 1: Huston-Algeciras-Dubai (Figure 8.4). It shows how, until December 2023, the logical passage of connection between Asia and Europe took place through the tandem of choke points between the Suez Canal and the Bab-al-Mandeb Strait. From that date on, instabilities with the Yemeni Houthis in the area began and it is observed that from January 2024 the route changes to circumnavigate Africa through the Cape of Good Hope.

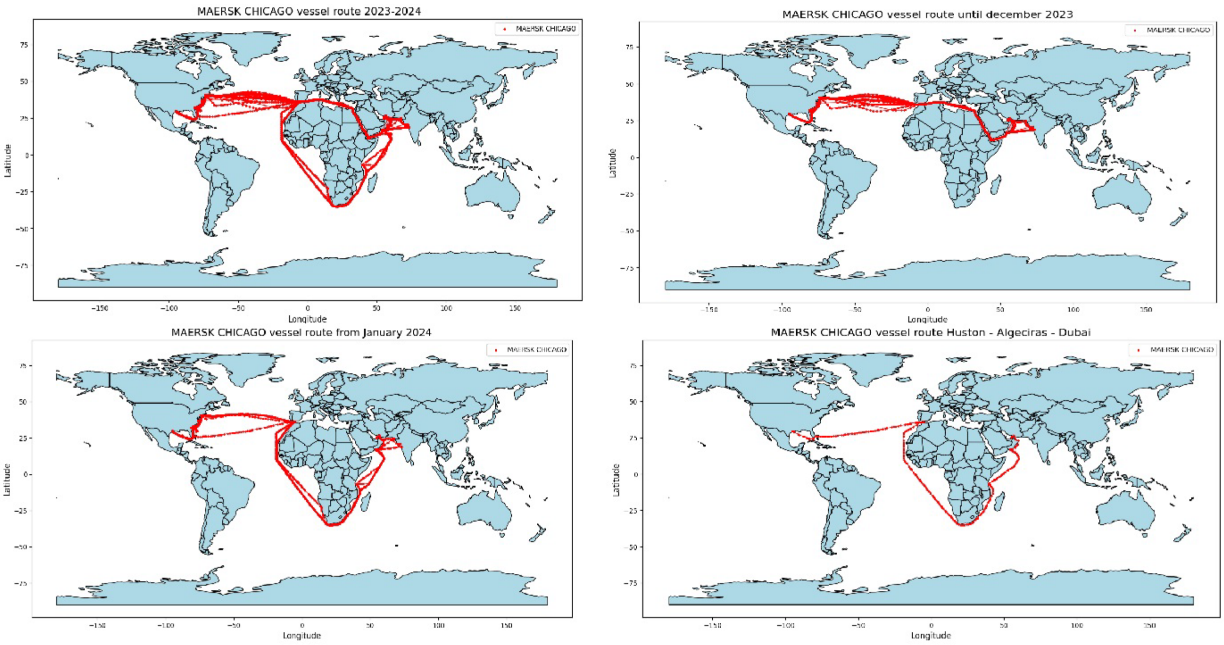


Figure 8.4: Maersk Chicago vessel GPS position. Source: own elaboration, data: SBC.

Following the indications of the European directive [173], the ETS calculation is made following formula 1:

$$Cost\ ETS = \sum_{i=1}^{n} \left(d \times \emptyset \times \frac{e}{1000} \times \mu \right) \qquad (1)$$

Being:

- n: number of annual stopovers subject to ETS.
- d: the distance in nautical miles travelled between ports
- $\emptyset$: Situation factor of the ports. If the port of departure is a non-European port, the factor is 0, if it is a transparent port it is 0.5 and if it is European, 1.
- e: emissions reported by the ship in MRV ($kg\ CO_2/mn$)
- μ: cost of the allowance ($€/tonCO_2$)

With all this, the following tables are obtained (Table 8.2, Table 8.3, Table 8.4)

Table 8.2: Results of the application of the ETS in scenario 1. Source: Own elaboration.

SCENARIO 1- NORTH AMERICA-EAST ROUTE (HUSTON - ALGECIRAS - DUBAI)

scenario	Circunavigation	Port of Origin	Non-European Port	Destination Port	Leg 1 (nm)	Leg 2 (nm)	ETS Price (€/ton)	Leg Factor 1	Leg Factor 2	CO2 Emissions Factor (kg CO2/nm)	CO2 Emissions (ton)	Price Leg 1	Price Leg 2	Cost
E 1.1	No	Huston	Algeciras	Dubai	5423	4806	69.38	0.5	0,5	597	3053.3565	€112,309.95	€99,531.92	€211,841.87
E 1.2	Yes	Huston	Algeciras	Dubai	5423	9831	69.38	0.5	0,5	597	4553.319	€112,309.95	€203,599.32	€315,909.27
E 1.3	No	Huston	Tanger	Dubai	5423	4806	69.38	0	0	597	0	€0.00	€0.00	€0.00
E 1.4	Yes	Huston	Tanger	Dubai	5423	9831	69.38	0	0	597	0	€0.00	€0.00	€0.00

Table 8.3: Results of the application of the ETS in scenario 2. Source: Own elaboration.

SCENARIO 2- NORTH AMERICA-NORTH EUROPE ROUTE (MONTREAL - LIVERPOOL - LE HAVRE)

scenario	Situation	Port of Origin	Non-European Port	Destination Port	Leg 1 (nm)	Leg 2 (nm)	ETS Price (€/ton)	Leg Factor 1	Leg Factor 2	CO2 Emissions Factor (kg CO2/nm)	CO2 Emissions (ton)	Price Leg 1	Price Leg 2	Cost
E 2.1		Montreal		Le Havre	3103		69.38	0.5		1027	1593.3905	€110,549.43	€0.00	€110,549.43
E 2.2		Montreal	Liverpool	Le Havre	2795.13	501	69.38	0	0.5	1027	257.2635	€0.00	€17,848.94	€17,848.94
E 2.3	If Liverpool were a Transparent Port	Montreal		Le Havre	3103		69.38	0.5		1027	1593.3905	€110,549.43	€0.00	€110,549.43
E 2.4		Montreal	Liverpool	Le Havre	2795.13	501	69.38	0.5	0,5	1027	1692.56276	€99,581.06	€17,848.94	€117,430.00

Table 8.4: Results of the application of the ETS in scenario 3. Source: Own elaboration.

SCENARIO 3- ASIA-MEDITERRANEAN-NORTH EUROPE ROUTE (SINGAPORE - ALGECIRAS - ROTTERDAM)														
scenario	Circunavigation	Port of Origin	Non-European Port	Destination Port	Leg 1 (nm)	Leg 2 (nm)	ETS Price (€/ton)	Leg Factor 1	Leg Factor 2	CO2 Emissions Factor (kg CO2/nm)	CO2 Emissions (ton)	Price Leg 1	Price Leg 2	Cost
E 3.1	No	Singapore	Algeciras	Rotterdam	6889,98	1353.17	69.38	0.5	1	1027	4927.71032	€245,466.77	€96,417.77	€341,884.54
E 3.2	Yes	Singapore	Algeciras	Rotterdam	10694,69	1353.17	69.38	0.5	1	1027	6881.42891	€381,015.76	€96,417.77	€477,433.54
E 3.3	No	Singapore	Tanger	Rotterdam	6950,01	1339.36	69.38	0.5	0.5	1027	4256.5915	€247,605.43	€47,716.88	€295,322.32
E 3.4	Yes	Singapore	Tanger	Rotterdam	10669,83	1339.36	69.38	0.5	0.5	1027	6166.71907	€380,130.09	€47,716.88	€427,846.97

Table 8.2 shows the calculations made for Scenario 1. In this case, the ship that makes the European Huston-Algeciras-Dubai route between legs and whose emission factor has been obtained from the emissions declared by the ship in the year 2023 in the MRV is studied [174]. The ETS price (€/ton CO2) for all scenarios has been obtained from trading economics in July 2024. The circumnavigation casuistry of the African continent is taken into account, which implies an increase in the crossing distance by 49.1%. The cost of making a stopover in a European port on the route on which the ship circumnavigates Africa is €104,067.40, higher than the passage of the Suez Canal. On the other hand, in the event that due to the cost of ETS the ship decides to make an intermediate call in Tangier, a non-European port, 100% of the costs would be saved since none of the legs of the crossing would call at a port subject to ETS. This represents a saving of €211,841.87 if circumnavigation is not carried out and €315,909.27 if it is carried out (Figure 8.5).

Figure 8.5: Cost difference in scenario comparison 1. Source: own elaboration.

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Table 8.3, belonging to Scenario 2, studies a ship that makes the Montreal-Liverpool-Le Havre route. In this scenario, the aim is to analyse the influence of including a call at a port in the United Kingdom for routes between North America and northern Europe. It can be seen that a ship between Montreal and Le Havre would pay 50% of the emissions produced on that route, but if Liverpool, a non-European port, is included, the emissions subject to ETS would become only 50% of those produced in the approximately 500 nautical miles (n.m.) between Liverpool and the French coast, which represents a saving per stopover of €92,700.49. In the event that in the future the European Union includes this British port (as it already has others), modifying the criteria, in the transparent list of ports (currently the criteria are that they are located less than 300 n.m. from the European port and that they carry out a transshipment activity equal to or greater than 65%) it is observed that the stopover in Liverpool, to travel more miles, this carbon leakage could not occur because it would not be economically profitable for the shipping company (Figure 8.6).

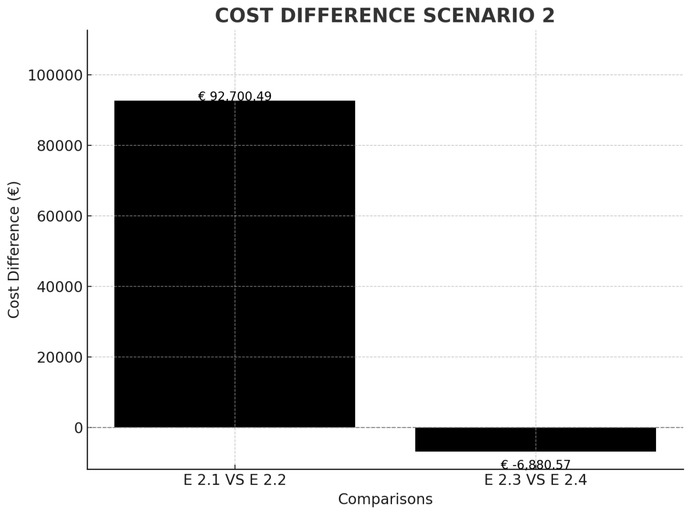

Figure 8.6: Cost difference in scenario comparison 2. Source: own elaboration.

Finally, Table 8.4 nshows the results of the Maersk A2 route between Singapore-Algeciras-Rotterdam (Asia-Mediterranean-Northern Europe) of Scenario 3. Two main cases are shown, the first as the increase in crossing to circumnavigate Africa means an increase in emission rights costs of € 135,549.00 per stopover. On the other hand, the possibility is being studied that the shipping company in question decides, due to the cost of calling at a European port such as Algeciras, to change and start calling in Tangier (a port located on the same route with zero deviation). As Tangier is a port classified as transparent by the EU, the ship would pay 50% of the emissions for the Singapore-Tangier route and 50% for the emissions of Tangier-Rotterdam. This change would mean the shipping company now approximately €46,562.22 per stopover and vessel (Figure 8.7).

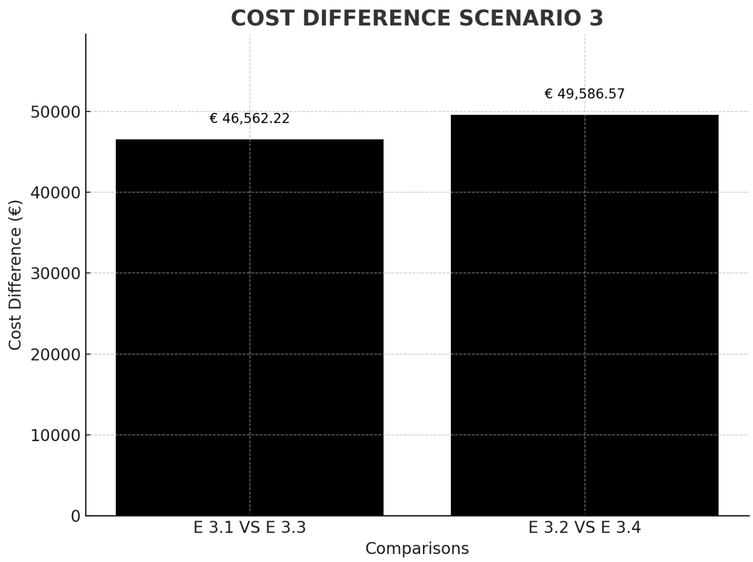

Figure 8.7: Cost difference in scenario comparison 3. Source: own elaboration.

8.5. Conclusions

It is clear that the Emissions Trading System (ETS) represents one of the main tools that the European Union has implemented to move towards the continent's energy transition. However, it is critical to develop a clear proposal for how the funds raised through this system will be allocated. These resources could be channeled towards the promotion of green technologies and the energy transition in shipping companies, ports, and other key agents in the logistics chain, thus ensuring a positive and equitable impact. Additionally, specific legislative measures could be considered, such as fiscal incentives or direct subsidies for the ports most affected by the loss of competitiveness due to the ETS. A portion of the funds raised could also be allocated to modernizing port infrastructures and fostering the transition to sustainable fuels.

The results obtained meet the objective of the research and show that the maritime trade of European ports will be affected, especially those that have close competitors in regions outside the EU, which could erode their competitiveness. In this context, the concept of "transparent port" could require a revision, adjusting the inclusion criteria to incorporate ports that, while not currently meeting the threshold of 65% transshipment or located more than 300 nautical miles from a European port, represent direct competitors in terms of carbon leakage (such as certain African or British ports). Legislative adjustments to redefine these criteria could include such relevant ports based on their competitive relevance rather than geographical proximity or current transshipment percentages.

Although a readjustment of routes and a possible loss of traffic in the coming years is foreseeable, this change will not be immediate. In 2024, only 40% of emissions will be paid, rising to 70% in 2025 and reaching 100% in 2026. Therefore, the real impact on shipping routes and traffic is not likely to be fully reflected for two to three years, as shipping companies consider multiple factors when designing their logistics chains.

One of the main challenges encountered during this research was limited access to up-to-date, real-time data on ship emissions. The large amount of data required underscores the need for big data analysis, which would allow for a more comprehensive and detailed study of a larger part of the global fleet.

Future lines of research could focus on expanding the scope of the study, including a greater number of routes and vessels. In addition, the impact of the United Kingdom, not being part of the EU and not applying the ETS, which could influence northern European ports, must be considered. It would also be relevant to analyze the evolution of stopovers and route changes using satellite information, to gain a more detailed understanding of how ETS affects maritime operations.

Finally, from an environmental perspective, it would be interesting to explore how ETS could influence Short Sea Shipping (SSS) routes. As these routes are fully subject to 100% emissions from 2026, it could be economically unfeasible for some shipping companies to maintain such operations, which could reverse some progress made in terms of decarbonizing land transport and increase emissions again due to greater road traffic.

Abbreviation list:

- ETS - Emissions Trading System
- EU - European Union
- EEA - European Economic Area
- CO_2 - Carbon Dioxide
- MRV - Monitoring, Reporting, and Verification
- IMO - International Maritime Organization
- ECA - Emission Control Area
- GT - Gross Tonnage
- LNG - Liquefied Natural Gas
- AFIR - Alternative Fuels Infrastructure Regulation
- SSS - Short Sea Shipping
- CH_4 - Methane
- NOx - Nitrogen Oxides
- n.m. - Nautical Miles
- SDGs - Sustainable Development Goals

9. CASE STUDY 2: BAYESIAN NETWORKS FOR ASSESSING THE SUSTAINABILITY OF THE MARINE RENEWABLE ENERGY SECTOR IN THE BLUE ECONOMY OF SPANISH PORTS

This chapter presents the accepted manuscript of RA4 that has been published in a peer-reviewed and indexed journal:

Vaca-Cabrero, J., González-Cancelas, N., & Camarero-Orive, A. (2025). Bayesian networks for assessing the sustainability of the Marine Renewable Energy sector in the Blue Economy of spanish ports. *Sustainable Futures*, 100497. https://doi.org/10.1016/j.sftr.2025.100497

Abstract: This research focuses on identifying key indicators for the sustainable development of the Marine Renewable Energy sector in the Blue Economy of Spanish ports, utilizing Bayesian networks to integrate economic, social, and environmental perspectives. The study also aims to develop a decision-support tool for strategic planning in ports. The methodology involves creating and analyzing a Bayesian model using data from 28 Spanish port authorities. The study includes selecting indicators, data preprocessing, and model construction to identify interrelations among sustainability variables. Key findings indicate that economic investment in port infrastructure, environmental characterization, and occupational safety are crucial factors for the sector's development. Bayesian networks enabled the representation of relationships among these indicators, highlighting the importance of a balanced approach between economic, social, and environmental sustainability. The study concludes that the sustainability of the Marine Renewable Energy sector depends on an effective integration of economic investments, environmental management, and occupational safety measures, supported by tools like Bayesian networks to optimize decision-making in the port sector.

Keywords: Bayesian Networks; Blue Economy; Marine renewable energies; Sustainability; Spanish ports.

9.1. Introduction

The development of the Blue Economy, understood as an economic model that promotes the sustainable use of ocean resources to drive economic growth, improve livelihoods, and preserve marine ecosystems, is essential for European ports, particularly in the marine renewable energy sector. This economy promotes the sustainable management of ocean resources, fostering innovation and economic growth o [11]. Ports play a fundamental role as hubs for the development of marine renewable energies, fostering the energy transition and reducing pollution. This strategy strengthens both port competitiveness and the sustainable development of European coastal regions, significantly contributing to achieving sustainability objectives and ensuring the future of the maritime sector[7].

The Marine Renewable Energy sector is one of the nine sectors of the Blue Economy recognized by the European Commission in the 2024 report, highlighting activities such as offshore wind energy [13]. The Blue Economy is crucial for the future development of European ports, contributing significantly to the European

Union's energy transition, supporting decarbonization objectives, and reducing dependence on fossil fuels. Additionally, it fosters sustainable economic growth, creates employment opportunities, and strengthens port competitiveness by integrating clean energy sources. Ports, as centers of logistics and operations, will play a key role in the expansion of these technologies, promoting both the Blue Economy and environmental sustainability.

Port sustainability requires an integrated approach that encompasses economic, social, and environmental dimensions. From an economic perspective, the implementation of renewable energies and more efficient technologies can reduce long-term operational costs and strengthen port competitiveness [175]. Occasionally, port planning must incorporate community participation and promote activities that generate local employment, seeking to maximize the social benefits of port activities [176]. Moreover, from an environmental perspective, it is crucial to adopt measures that minimize emissions and impacts on marine ecosystems, as well as manage the land-intensive use of port infrastructure. Ports, as significant energy consumers and sources of pollution, must integrate clean technologies and environmental management practices to reduce their ecological footprint [31]. In summary, a sustainable port is one that balances economic efficiency with social benefits and environmental protection, thereby fostering holistic and enduring development.

The development of the Blue Economy is fully aligned with European sustainable development policies, such as the Green Deal and the "Fit for 55" package. The Blue Economy, which includes the Marine Renewable Energy sector, promotes the transition towards a clean energy model in European ports, crucial for reducing carbon emissions and achieving the European Union's decarbonization goals. Initiatives such as offshore wind energy contribute not only to reducing dependence on fossil fuels but also to promoting sustainable economic growth and job creation [13]. Ports, considered as logistical and operational hubs, are fundamental to achieving these goals, acting as catalysts for innovation and energy efficiency, supporting the "Fit for 55" objectives to reduce emissions by 55% by 2030[177], [5]. Integrating economic, social, and environmental sustainability into port development is essential to enhance competitiveness, minimize environmental impact, and ensure equitable growth that benefits local communities [6]. In this context, European ports are aligned with the commitments of the Green Deal to foster a fair and sustainable transition towards a more resilient and low-carbon future.

The main objective of this research is to identify key sustainability indicators for the development of the Marine Renewable Energy sector within the Blue Economy of Spanish ports using Bayesian networks. The goal is to determine which factors are the most influential from an integrated perspective encompassing economic, social, and environmental dimensions. A secondary objective is to develop a decision-support tool for strategic planning in ports, promoting balanced and sustainable sectoral development. The motivation for this article lies in the need to promote sustainability in a key sector for Europe's energy transition, thereby contributing to meeting climate goals and strengthening the competitiveness of ports as key actors in the Blue Economy.

The article is structured as follows: the "State of the Art" section presents a literature review related to port sustainability, the Marine Renewable Energy sector, and the use of Bayesian networks in sustainability studies. The "Methodology" section describes the employed approach, covering aspects from the selection of the study scope to the construction of the Bayesian model. The "Results and Analysis" section presents the obtained findings and discusses their implications for sustainable sectoral development. Finally, the "Conclusions" highlight the contributions of the research and propose directions for future studies.

9.2. State of the art

9.2.1. Port Sustainability

Studies on port sustainability provide a comprehensive view of the current state, challenges, and opportunities faced by ports to progress towards more sustainable development. It is identified one of the main challenges as the lack of consistency in measurements and the difficulty of implementing sustainable strategies homogeneously across different regions [31]. Similarly, there are proposals to create a framework based on the United Nations Sustainable Development Goals (SDGs), allowing port sustainability actions and measures to be categorized into environmental, economic, and social domains [1]. However, a major challenge is the limited adoption of sustainable practices due to a lack of resources and clear policies. In the social aspect of sustainability, the importance of involving local communities in the construction of sustainability indicators is highlighted, emphasizing that ports should align with stakeholder priorities to ensure success in sustainable management [28].

Regarding opportunities, there are innovative tools for evaluating port sustainability comprehensively. An example is the application of the End-to-End tool to assess a fishing port, such as the port of Vigo, Spain, demonstrating that the analysis of environmental, economic, and social aspects helps identify key areas for improvement and promote more effective ecological practices[8]. Studies on other facilities closely linked to ports, such as dry ports, also highlight the opportunity to deepen less explored research areas and strengthen collaboration among actors involved in sustainability [34]. All studies converge in concluding that ports have a crucial role in transitioning towards a sustainable future, requiring effective coordination, improvements in indicator measurement, and a holistic approach that integrates all stakeholders in the process.

9.2.2. Marine Renewable Energy sector and its implication in ports

Recent studies on integrating marine renewable energies into ports highlight both the challenges and opportunities this transition offers towards port sustainability. From an international perspective on assessing the environmental effects of marine energy development, there is a need to better understand the interactions between these systems and the marine environment to mitigate potential negative impacts [178]. Similarly, the synthesis of the environmental effects of oceanic energy emphasizes the importance of a balanced approach that ensures both energy generation and ecosystem conservation [179]. Additionally, the dimension of marine space-use conflicts must be noted, highlighting that the growing competition for these spaces demands effective spatial planning to avoid conflicts with other sectors like fisheries and tourism [180].

Various studies also address the technical and economic viability of integrating renewable energies into specific ports. It is demonstrate the feasibility of harnessing wave energy to meet part of the energy demand at the port of Valencia, Spain, which not only reduces operational costs but also minimizes carbon emissions[181]. The use of tidal energy is also investigated, showing it can be a sufficient driver to achieve energy self-sufficiency at a port, indicating that harnessing local marine resources can lead to a significant reduction in fossil fuel dependence [182]. In a similar context, the use of marine renewable energy in

Middle Eastern ports is examined, highlighting the need to adapt technological solutions to the specific characteristics of each region [183].

In the context of Spain, the recently approved Maritime Spatial Planning Plans (POEMs) represent a fundamental strategic tool for sustainable maritime space management. These plans identify suitable areas for different uses, including marine renewable energy production, facilitating the creation of energy hubs in specific zones. POEMs promote spatial planning that optimizes the use of maritime space, minimizes conflicts with other sectors, and facilitates the integration of marine energy installations. Effective planning is key to transforming maritime areas into strategic points of clean energy generation, supporting both environmental sustainability and economic development of ports and coastal regions[184].

Finally, there are trends in collaborative approaches and technical perspectives for implementing these technologies. Buonomano et al. propose the creation of energy communities in ports, allowing shared production and management of renewable energy, optimizing local resources [185]. Additionally, various technologies such as solar, wind, and tidal energy are evaluated, considering their technical viability and economic profitability, and providing recommendations for ports to reduce their carbon footprint [67]. Collectively, these studies reinforce the idea that transitioning towards sustainable ports should include developing clean technologies and efficiently and collaboratively managing resources to ensure long-term environmental, economic, and social benefits.

9.2.3. Sustainability Indicators

Sustainability indicators are fundamental tools for assessing and monitoring the environmental, social, and economic performance of different sectors, such as cities, energy, tourism, and ports. They allow progress towards sustainable development goals to be measured, facilitating informed decision-making aligned with sustainability. These indicators can be classified into several types: environmental indicators that measure impact on the environment, social indicators that evaluate quality of life and equity, and economic indicators that analyze efficiency and economic growth [186].

Sustainability assessment is conducted through various methodologies, such as multicriteria analysis and life cycle assessment, which provide a comprehensive view of performance while emphasizing the importance of evaluating all sustainability dimensions [187]. In the port sector, there are proposals for a framework to report environmental indicators, aiming to harmonize sustainability assessment across ports [188]. The appropriate choice of indicators is crucial for tailoring the assessment to each specific context. An example is the assessment conducted in the Italian port system, which analyzed the economic and environmental efficiency of 13 Italian ports using Data Envelopment Analysis. The conclusion was that only some ports achieve optimal efficiency, while others exhibit inefficiencies. Recommendations include adopting green technologies and improving operational management to balance sustainability and competitiveness ([189].

These indicators allow progress to be monitored, inform decision-making, and promote transparency. In the port context, these indicators help align port practices with international commitments and allow for the evaluation of port operations' impact on key sustainability dimensions, such as emission reductions and energy efficiency [190]. In summary, sustainability indicators are vital tools for guiding the transition towards more balanced and responsible development across various sectors, particularly the port sector.

9.2.4. Bayesian Networks in Sustainability Studies

Bayesian Networks (BNs) are probabilistic tools useful for representing dependency relationships between variables and managing uncertainty in complex systems, which has promoted their use in sustainability studies. In sustainable environmental management, BNs are highlighted as a participatory approach that facilitates the integration of knowledge from multiple actors to better understand complex environmental systems, contributing to addressing environmental challenges in a more holistic manner [191].

In the social sustainability domain, BNs are used to evaluate the social impact of infrastructure projects. This approach allows for analyzing different design alternatives and mitigating potential negative effects on communities, ensuring more balanced and sustainable planning[192]. BNs are also applied in the evaluation of watershed sustainability, integrating environmental and socio-economic variables to sustainably manage resources in the Hablehrood river basin [193]. This type of assessment demonstrates the ability of BNs to manage multiple interrelated factors.

in supply chain sustainability, multi-level BNs are employed to evaluate the sustainability of a supply network, considering economic, environmental, and social aspects. This allows identifying areas for improvement and conducting comprehensive evaluations in logistics [194]. Additionally, BNs are used to develop a model for assessing the resilience of urban transportation systems, providing a key tool for planning and managing urban mobility in a sustainable and resilient manner [195].

In the renewable energy sector, BNs are used for risk analysis in the wind energy industry, which helps improve the sustainability and reliability of energy systems [196]. Moreover, BNs are applied to explore interrelationships between Sustainable Development Goal 6 (clean water and sanitation) and other goals of the 2030 Agenda, providing a deeper understanding of synergies and trade-offs in policy implementation [197].

In the port context, BNs have been applied to classify and predict port variables, improving port management and operational efficiency. The results demonstrate the effectiveness of this approach in strategic decision-making in the port domain [49].

In summary, BNs are fundamental tools in sustainability evaluation and planning, allowing the integration of various variables and the management of uncertainty in decision-making processes to advance towards more sustainable development in multiple sectors.

9.2.5. Research Gap

The literature review identifies a significant gap in studies on port sustainability and marine renewable energy. Although there is considerable focus on environmental sustainability and energy efficiency in ports, there is a lack of analysis that integrates environmental, economic, and social dimensions. Additionally, studies tend to focus on port sustainability solely within the infrastructure scope, without addressing the crucial role ports can play as platforms for developing offshore renewable energies.

This research seeks to address these gaps by using Bayesian Networks to identify and analyze the most influential sustainability indicators for developing marine renewable energies as a sector of the Blue Economy. The proposed approach considers ports as true centers for driving offshore energy, assessing their capacities not only from an environmental perspective but also considering socioeconomic impacts. This way, the study provides a more balanced and holistic analysis, highlighting the importance of ports in transitioning to a sustainable energy model that also generates economic and social opportunities at both local and regional/national levels.

9.3. Methodology

In this chapter, the phases followed in the research are presented. These phases are schematically outlined in Figure 9.1.

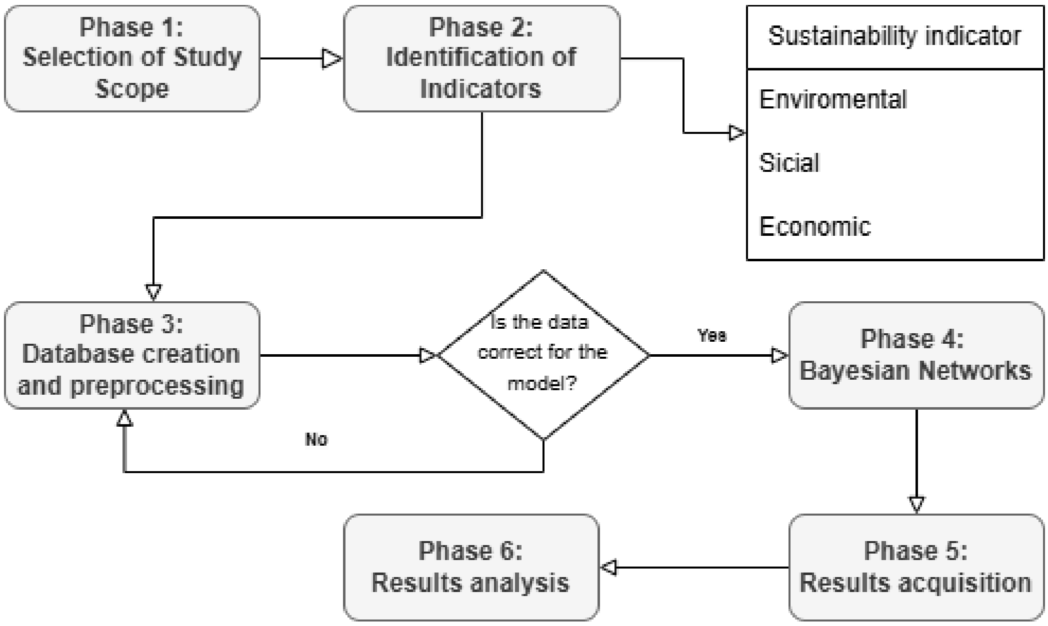

Figure 9.1: Researching chart flow. Source: own elaboration.

9.3.1. Phase 0: Research Design

The design of this research is descriptive and exploratory. The method employed is suitable for the objective since it describes the interrelations between environmental, social, and economic sustainability indicators, and explores which of them are most influential in the development of the Marine Renewable Energy sector in Spanish ports. This approach allows not only the understanding of existing patterns but also the identification and prediction of new opportunities to enhance the sustainable development of the Blue Economy.

9.3.2. Phase 1: Selection of Study Scope

In this research, the study scope includes all 28 port authorities of the Spanish system, ensuring sufficient representativeness and relevance for the development of the Marine Renewable Energy sector. By including all port authorities, ports from various coastal regions of Spain are represented, thus reflecting the heterogeneity of the Spanish port system. Different types of port districts with their infrastructures are also represented, ensuring the versatility and suitability of facilities dedicated to aspects closely related to marine renewable energies, such as wind and tidal energy.

9.3.3. Phase 2: Identification of Indicators

As a necessary step to construct the Bayesian network, environmental, social, and economic sustainability indicators were identified and selected. These indicators include aspects such as local employment creation, investments in environmental characterization, number of jobs in the port, etc. The selection of these indicators was based on official sources from the public entity Puertos del Estado, such as port sustainability and economic reports, all of this information is open data.

9.3.4. Phase 3: Database Creation and Preprocessing

In this phase, the time series of indicator data on an annual scale was collected. Next, data preprocessing was carried out to facilitate model application:

- Encoding categorical data into numerical form.
- Normalizing values.
- Discretizing values into five intervals.

9.3.5. Phase 4: Bayesian networks.

Definition and Justification

Bayesian networks were chosen as the main tool due to their ability to model dependency relationships between variables and handle uncertainty, which is crucial in this type of study where multiple factors are interrelated [49]. This technique allows the identification of conditional relationships between different indicators and the evaluation of which are most influential in the development of the Marine Renewable Energy sector within the Blue Economy. These probabilistic networks are based on Bayes' theorem. The general formula for calculating the probability of a series of variables (nodes) is as follows (Formula 1):

$$P(X_1, X_2, \ldots, X_n) = \prod_{i=1}^{n} P\big(X_i \big| Pa(X_i)\big) \qquad (Formula\ 1)$$

Where:

- $X_1, X_2, \ldots, X_n$ are the variables of the Bayesian network.
- $P\big(X_i \big| Pa(X_i)\big)$ epresents the conditional probability of variable X_i, given its parent set $Pa(X_i)$, which are the nodes that have a direct connection to X_i.

Model Construction

The Bayesian network model was built using the pgmpy software [198], Python library specialized in probabilistic networks. A network structure was established that includes the selected indicators as nodes, and the connections between these represent dependency relationships. To define the structure, techniques based on expert knowledge and analysis of historical data from the selected ports were used.

9.3.6. Phase 5: Results Acquisition

The initial results obtained from the model graphically displayed all possible probabilistic relationships between the nodes. The network was subsequently pruned in several iterations using expert criteria to discard weak relationships, resulting in the final network.

9.3.7. Phase 6: Results and Analysis.

In this final phase of the research, the final results were obtained and analyzed. The data analysis included descriptive statistical techniques to determine the relationships between the indicators. This approach allowed the identification of key indicators and provided practical recommendations for optimizing efforts in the development of the Marine Renewable Energy sector from a sustainable perspective.

9.4. Results and analysis of the results

The results begin by applying the Bayesian network method to the database. Initially, there were 49 indicators (variables) used to run the model, and after the first preprocessing and analysis, 15 variables with 46 interdependencies were obtained (Figure 9.2).

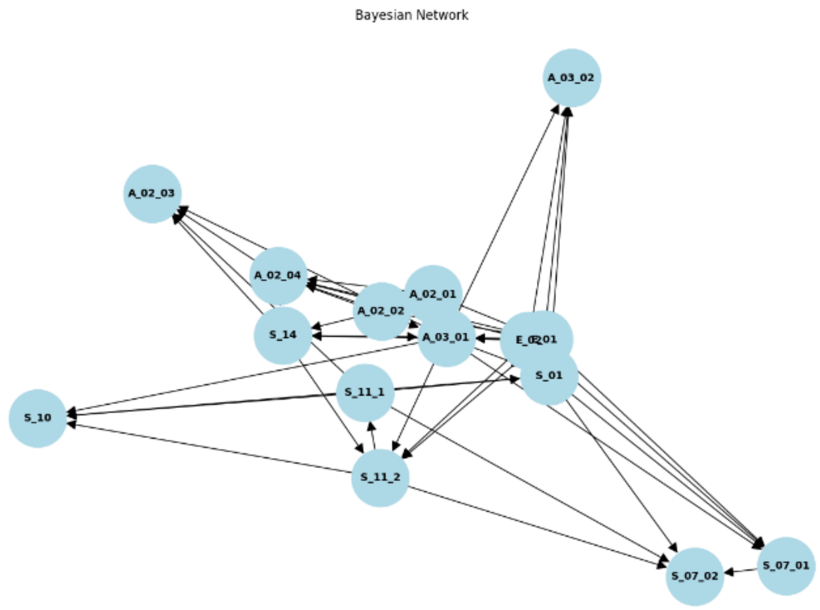

Figure 9.2: Origianl Bayesian Network . Source: own elaboration.

In Figure 9.2, several cross-connections between nodes can be observed, indicating a complexity within the Bayesian network. This can result from strong relationships or mutual dependencies between some variables. Cross-connections often suggest that multiple nodes are correlated and influence each other, making interpretation difficult without a clear hierarchy.

Therefore, it is evident that pruning the network under expert criteria and establishing a hierarchical structure are necessary, where the upper level includes the network parents and the lower levels contain the child nodes and their interrelationships. This is complemented with the use of an adjacency matrix to identify the less significant interconnections. The main objective is to simplify the network structure, improving interpretability and efficiency without sacrificing predictive capability. The adjacency matrix helps visualize weaker or redundant connections, facilitating an informed pruning. This reduces the model's complexity by removing arcs and nodes that do not significantly contribute to understanding or predicting variable behavior. The result is a more manageable network with a reduced risk of overfitting, improved computational performance, and a clearer structure that highlights key relationships within the modeled system.

After several iterations of pruning and improving the graphical interpretation of the model, the transition from a complex and difficult-to-interpret network (Figure

9.3) to a manageable one that justifies decision-making with fewer variables (Figure 9.4) is achieved.

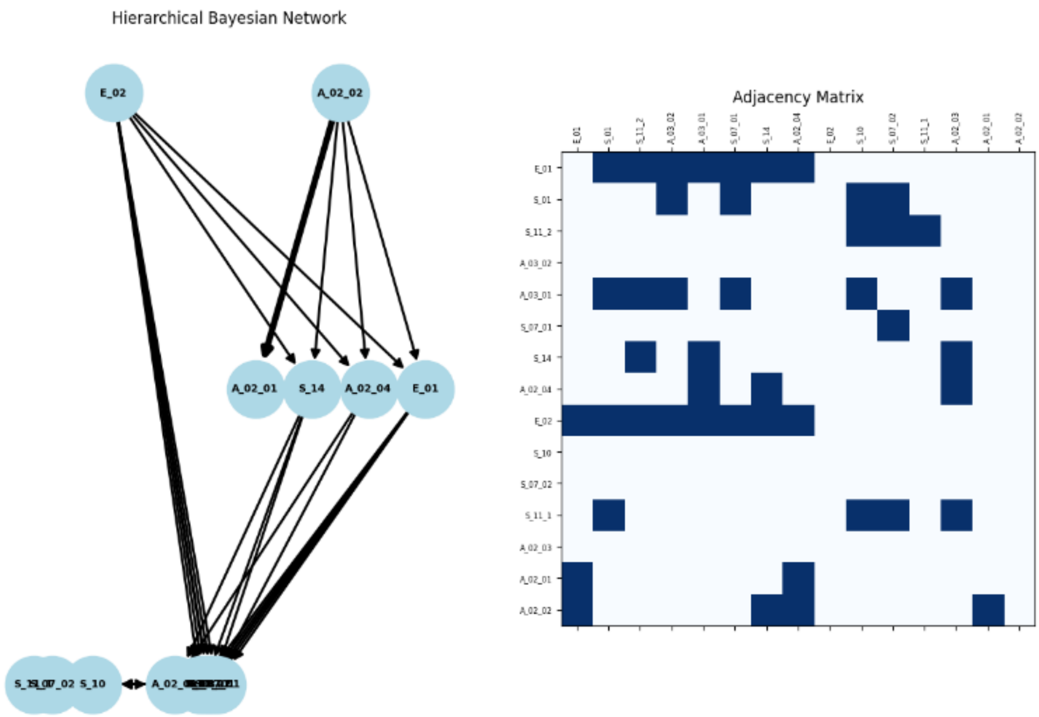

Figure 9.3: Original Hireachical Bayesioan Network (left) and Adjacency matrix (right) original. Source: own elaboration.

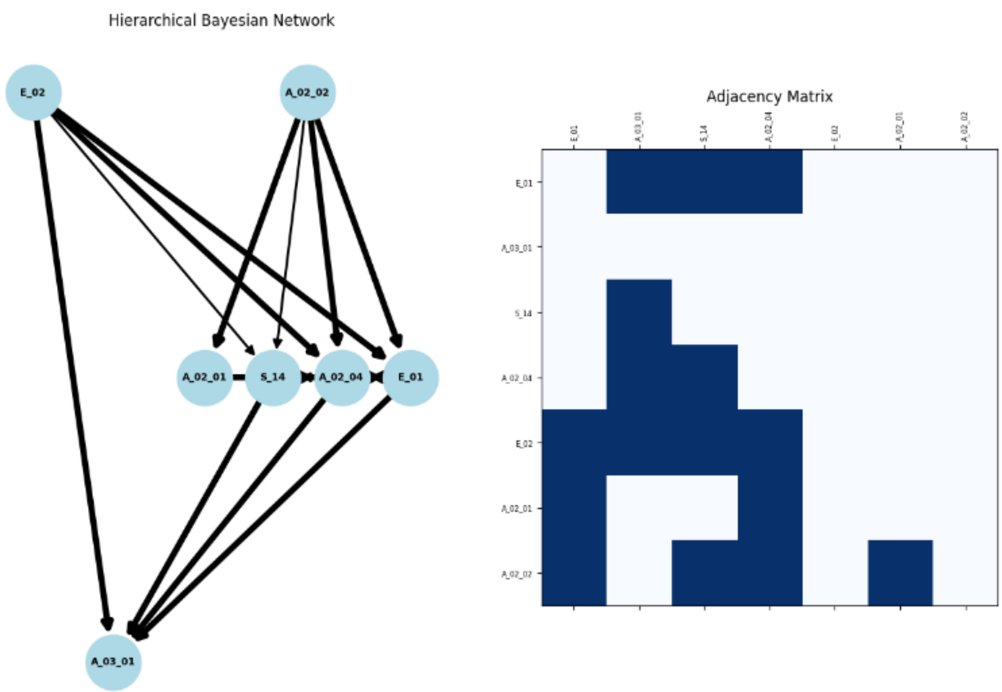

Figure 9.4: Pruned Hireachical Bayesian Network (left) and Adjacency matrix (right) original. Source: own elaboration.

The hierarchical Bayesian network obtained in Figure 9.4shows a clearer and simpler structure after pruning. Key nodes, such as E_02 and A_02_02, appear as influential variables with multiple connections to other nodes, suggesting their relevance within the network; they are categorized as the network's parents. This hierarchical organization facilitates the interpretation of parent-child relationships (from higher to lower levels) and reduces model complexity, making it more evident how dependencies flow through the structure. Nodes with multiple parents, such as A_02_04 and S_14, reflect the existence of multiple factors influencing these variables. The thickness of relationship lines also deserves attention, as greater thickness indicates a stronger dependence between variables.

Comparing the evolution from Figure 9.3 to Figure 9.4, it is clear that many relationships have been eliminated without any loss of information, allowing the focus on the most relevant connections and improving efficiency, achieving a balance between model simplicity and the preservation of important relationships.

Next, the resulting variables from the final pruning of the model are analyzed. Table 9.1 shows the final seven indicators, ordered from highest to lowest weight in the network.

Table 9.1: Results and characterization of the predominant variables obtained in the Bayesian network model.

Code	*Category*	*Variable*	*Justification of the variable*
E_02	Economic	Evolution of total investments in accruals	It reflects the financial capacity and availability of resources for the development of infrastructures and technologies in marine renewable energy, being essential to promote the sustainable growth of the sector.
A_02-02	Environmental	% of investment in environmental characterization with respect to the total	Investment in environmental characterization ensures a detailed assessment of the marine environment and minimizes environmental impacts by ensuring the sustainability of renewable energy development.
A_02_01	Environmental	Investment in environmental characterization	It derives from indicator A_02_02, directly indicating the resources dedicated to environmental characterization.
E_01	Economic	Evolution of property, plant and equipment in accruals	The development of the sector depends on a robust and modern port infrastructure. This variable reflects investment in tangible assets that are key to supporting marine renewable energy facilities and their growth in the port.
A_02_04	Environmental	% of expenditure on environmental characterization	Controlling expenditure on environmental characterization is important to ensure that resources are allocated sufficiently and appropriately to protect the marine environment and ensure the viability of renewable energy projects.
S_14	Social	Annual accident frequency rate	Workplace accidents on offshore projects are a major risk, and monitoring the frequency index is essential to improve safety and protect the workers involved.
A_03_01	Environmental	Expenses in € in cleaning of port areas	The cleanliness of the port is crucial to maintain a healthy environment and minimize the negative effects of industrial activities, supporting a sustainable development of marine renewable energy projects.

The results presented in Table 9.1 highlight a set of key variables that characterize the sustainable development of the marine renewable energy sector within the blue economy of ports in the Spanish port system. Specifically, economic, environmental, and social aspects are identified as playing a fundamental role in the sector's evolution. Economic variables (2 out of 7), such as "Evolution of total investments in accruals" and "Fixed assets in accruals," reflect the importance of consistent and efficient infrastructure investment, which is essential to support the sector's growth. These investments facilitate the modernization and adaptation of port areas and the implementation of technologies that enable the integration of renewable energies.

On the other hand, environmental variables (4 out of 7) and social variables (1 out of 7) underline the need for a balanced approach between economic growth and environmental and social responsibility. Investment in environmental characterization helps mitigate the negative impacts of port activities. Additionally, the "annual accident frequency rate" is a key indicator in the social dimension, as occupational safety in projects such as offshore energy must be a priority for sustainable development. Overall, these results emphasize that the development of the marine renewable energy sector depends not only on adequate economic investment but also on proactive environmental management and the implementation of effective occupational safety measures.

9.5. Conclusions

The conclusions of this research demonstrate that the main objective has been met: identifying, through the use of Bayesian networks, the most determining indicators for the sustainable development of the Marine Renewable Energy sector within the blue economy of ports in the Spanish port system, which are mainly the Evolution of Total Investments and Economic Efforts in Environmental Characterization.

The obtained results provide evidence of the essential elements that must be strengthened to ensure the sustainable development of marine renewable energies in the context of Spanish ports. They offer a solid foundation for strategic decision-making aimed at promoting the balanced growth of the blue economy.

The applicability of the developed Bayesian model is demonstrated in its ability to provide a comprehensive and quantitative view of the interrelationships between different variables. This probabilistic tool not only allows for the analysis of direct relationships between sustainability indicators but also infers indirect dependencies and evaluates the potential impact of various strategic decisions. Its implementation in port management will facilitate planning and prioritization of investments in critical areas, optimizing available resources, and improving responsiveness to environmental and socio-economic challenges that may arise during the energy transition process.

One of the novel aspects of this work lies in the application of Bayesian networks as a modelling tool for the sustainability of the marine renewable energy sector. It facilitates decision-making under uncertainty, a common scenario in resource management in the port environment. The ability of Bayesian networks to represent and quantify the dependency relationships between variables offers a significant advantage over more traditional approaches, providing a more dynamic and flexible analysis.

Additionally, the innovative use of specific sustainability indicators for the Spanish port system in the context of the development of the Blue Economy is another added value of this research. By focusing on indicators that reflect the specific realities of ports, this study provides an accurate evaluation of how renewable energy activities can be developed more sustainably. The selected economic, social, and environmental indicators provide a framework that integrates the triple sustainability balance and allows ports to identify key areas of improvement, such as investment efforts, environmental characterization, and worker safety.

Thus, the importance of an integrated and balanced vision of port development is established, encompassing economic, environmental, and social aspects, closing the identified research gap outlined in the state of the art.

This research has faced some limitations mainly related to data acquisition. The lack of data homogeneity or the large volume of mainly environmental indicator data made it necessary to preprocess the database to adjust it as closely as possible to the model's input needs. In terms of future directions, the implementation of this model in other international port contexts and in a greater number of Blue Economy sectors is proposed. To add more value to the research, it would be optimal to promote the measurement and integration of more dynamic, real-time indicators that allow the evaluation of the impact of specific policies and actions over time with greater precision. It would also be appropriate to generate an open data repository of indicators for future research.

The analysis conducted reveals that the marine renewable energy sector depends not only on adequate economic investment but also on proactive environmental management and the implementation of effective occupational safety measures. The use of Bayesian networks has enabled a deep analysis of these interrelationships, and the results obtained offer guidance for decision-making in planning the sustainable development of the sector. It is hoped that this approach can be replicated in other contexts and become a useful tool to enhance competitiveness, improve efficiency, and ensure a fair and sustainable transition towards a low-carbon future in European ports.

PART III: 10. GENERAL DISCUSION AND CONCLUSIONS

10. GENERAL DISCUSION AND CONCLUSION

Chapter 10 highlights the conclusions obtained from this thesis, both in the achievement of the objectives set and in the response to the initial research questions. In addition, the main limitations encountered during the development of the study are presented and future lines of research are proposed to delve into port sustainability, the Blue Economy and digitalization in broader contexts.

10.1. Conclusions

10.1.1. Summary of objectives and results achieved

The main objective of this thesis has been to analyse port sustainability through the integration of the principles of the Blue Economy and digitalisation in Spanish ports, with the aim of improving their efficiency and competitiveness. This objective was addressed through a multidimensional approach, which included five research questions aimed at exploring different key aspects: the implementation of the Blue Economy sectors, the impact of digital transformation, the relevance of the metaverse, the implications of the Emissions Trading System (ETS) and the sustainability of the marine renewable energy sector.

Firstly, a model was developed that made it possible to assess the degree of implementation of the Blue Economy sectors in Spanish ports. The results revealed significant disparities between different port authorities, highlighting that established sectors, such as coastal tourism and shipping, are at an advanced level of development, while emerging sectors, such as ocean energy and marine biotechnology, face strategic and financial constraints. This analysis underscores the need for more targeted policies that promote balanced growth in both types of sectors.

In the field of digital transformation, it was identified that tools such as digital twins and the metaverse are redefining port management. Digital twins have proven critical in optimizing operations, forecasting critical scenarios, and reducing operational costs, while the metaverse offers new opportunities for real-time virtual collaboration, increasing logistics efficiency and promoting sustainability. These technologies are presented as catalysts for an operational revolution that not only impacts competitiveness, but also the environmental commitment of ports.

In relation to digital governance, the analysis carried out with comprehensive tools, such as End-to-End tools, evidenced the importance of a collaborative approach that includes public and private actors. In addition, the relevance of training human capital trained in digital and sustainable skills was highlighted, as a determining factor to achieve the transition to smart and resilient ports.

The evaluation of the implementation of the ETS revealed significant challenges, particularly in economic terms, for port companies. However, opportunities for technological innovation were also identified, especially in the adoption of low-emission technologies and strategies for decarbonization. The results highlight that, while the ETS poses challenges in initial implementation, it could position European ports as leaders in the transition to more sustainable logistics models.

Finally, the use of Bayesian networks to assess the sustainability of the marine renewable energy sector made it possible to identify key indicators and develop robust predictive models. These tools proved to be effective in representing complex relationships between variables, facilitating informed strategic decision-making in an emerging sector that plays a fundamental role in port sustainability.

Taken together, the findings of this research emphasize the importance of taking a holistic approach that integrates environmental sustainability, technological innovation, and institutional collaboration. This approach is essential to position Spanish ports as global benchmarks in sustainability, efficiency and competitiveness, and to ensure their contribution to the development of a more balanced and responsible economy in the context of current and future challenges.

10.1.2. Reply to the Research Questions

The research carried out answers the RQ1 research question **"What is the degree of implementation of the Blue Economy sectors in Spanish ports and how does it vary between the different port authorities?"**, assessing the degree of implementation of Blue Economy sectors in Spanish ports and the variations between the different port authorities. The results obtained allow us to conclude that, although all ports actively promote the Blue Economy, there are significant inequalities in its development, which shows an unbalanced structure in the Spanish port system.

Firstly, the analysis confirms that the established sectors of the Blue Economy, such as coastal tourism, maritime transport and port activities, have a significantly higher level of development than the emerging sectors, reaching implementation levels above 95%. This difference is related to greater technological maturity, lower economic risk and a consolidated investment history in these sectors. However, emerging sectors, such as marine renewables and blue biotechnology, show levels of development below 50%, underscoring the need for a targeted strategy to boost their growth. This is especially relevant, given its transformative potential in economic diversification and environmental sustainability.

Regarding the disparities between port authorities, there is a significant gap in the levels of implementation. While ports such as Las Palmas lead the system with a 100% degree of implementation, others such as Villagarcía de Arosa and Gijón are more than 30 points below. These differences, which are not exclusively linked to the size or geographical location of ports, reflect a structural inequality that requires strategic attention to ensure more equitable development.

The research also concludes that port authorities that have made greater progress in the implementation of emerging sectors tend to generate more positive impacts in terms of sustainability and economic diversification. This reinforces the importance of prioritising these sectors in port policies and promoting support mechanisms that facilitate their integration into the strategic plans of port authorities.

To address these inequalities and foster a more balanced development, it is concluded that it is necessary to use the degree of implementation of the Blue Economy as a criterion for the distribution of resources in the Interport Compensation Fund. In addition, the creation of regional coalitions between ports with common objectives is recommended, such as the promotion of coastal tourism on the Mediterranean coast or the development of marine renewable energies on the Atlantic coast. These strategies would not only strengthen the capacity of individual ports, but also position the Spanish port system as a benchmark in the Blue Economy.

Finally, it is highlighted that the model developed in this study constitutes a useful tool to identify strengths and weaknesses in each port, and to carry out comparative analyses that inform strategic decision-making. This approach is not only applicable to Spanish ports, but can also be replicated in other international contexts, contributing to the global advancement of the Blue Economy.

In conclusion, this research not only provides a clear answer to the question posed, but also offers a framework for action. The existing disparities in the implementation of the Blue Economy represent both a challenge and an opportunity to strengthen the sustainability and competitiveness of Spanish ports. Promoting the development of emerging sectors and reducing inequalities between port authorities are essential steps to guarantee a sustainable and equitable future in the Spanish port system.

The **RQ2 research question, "How can digital technologies transform the operations, sustainability and competitiveness of Spanish ports in a global logistics**

environment?", has been answered through a detailed analysis of the current dynamics of port digitalisation, its benefits, challenges and its potential to redefine port management. The findings highlight that digital transformation not only improves operational efficiency and sustainability, but also strategically positions Spanish ports in the face of global trade challenges.

First, it concludes that the adoption of advanced technologies such as the Internet of Things (IoT), artificial intelligence, and digital twins has led to significant advances in operational efficiency. These tools have made it possible to reduce waiting times, optimize logistics management and facilitate more informed and proactive decision-making. However, critical challenges were also identified, such as limited interoperability between systems, cybersecurity, and a shortage of skilled personnel, which may restrict the expected benefits of digitalization.

In terms of sustainability, digital technologies have proven to be an essential ally in reducing the environmental impact of port activities. The electrification of the docks and the optimization of the use of resources through digital systems have contributed to reducing carbon emissions and promoting sustainable practices. However, the study also highlights that integrating sustainability into digital processes requires a strategic approach that aligns these initiatives with global goals such as the Sustainable Development Goals (SDGs).

On the other hand, the competitiveness of Spanish ports has been strengthened thanks to the implementation of digital solutions that improve the quality of service and attract new business opportunities. Ports that have adopted advanced technologies, such as Valencia, Algeciras and Barcelona, stand out as benchmarks in digitalisation and digital governance. However, there is also a significant disparity between ports in terms of digital development, underscoring the need for policies and strategies that foster interoperability and reduce existing gaps.

Among the most significant barriers identified are the lack of modern infrastructure, limited data storage capacity, and the absence of automation in certain key processes. It was also detected that the current regulatory frameworks, together with their lack of stability and clarity, hinder the implementation of digital technologies. These limitations not only affect the efficiency of the port system, but also impact its ability to adapt to a dynamic global environment.

To overcome these challenges, it is concluded that it is essential to promote digital governance policies that promote interoperability and collaboration between the 28 Spanish port authorities. This includes establishing common standards for data management, strengthening cybersecurity, and investing in continuing education programs for port staff. In addition, it is recommended to promote public-private partnerships that allow sharing resources and implementing technological solutions more efficiently.

A key aspect highlighted in the conclusions is the need to adopt a more comprehensive approach to strategic planning, combining technology with sustainability and competitiveness objectives. Digital tools must be used not only to optimize processes, but also to transform the port system into a model that promotes transparency, resilience and innovation.

In summary, digital transformation has the potential to position Spanish ports as leaders in the global logistics field, but this process requires overcoming structural and operational challenges. Digital technologies are not an isolated solution, but a means to achieve a more efficient, sustainable and competitive port system. To do this, it is necessary to establish clear regulatory frameworks, invest in infrastructure and training, and foster a culture of innovation and collaboration between the different actors in the sector. By addressing these priority areas, Spanish ports will be better prepared to meet the challenges of the future and take advantage of the opportunities offered by the ever-changing global economy.

The **RQ3 research question, "How can the metaverse transform operation, management, and collaboration in ports, promoting greater efficiency, sustainability, and global competitiveness?"**, has been answered by exploring the potential of the metaverse as a disruptive tool in the port environment. This analysis concludes that the metaverse has the potential to revolutionize the way ports operate, manage their resources and collaborate with key players in the supply chain, consolidating itself as a strategic component for the modernization and global competitiveness of Spanish ports.

In terms of **operation**, the metaverse makes it possible to simulate and optimize processes in a digital environment that replicates port operations in real time. Through the use of digital twins, augmented reality, and artificial intelligence, it is possible to predict scenarios, minimize downtime, and increase the efficiency of logistics operations. These technologies also facilitate the automation of systems for the transport and handling of goods, which not only increases productivity, but also reduces the risks associated with human intervention. In addition, the metaverse offers advanced capabilities for staff training, allowing them to interact with simulations of complex scenarios, improving safety and reducing operational errors.

When it comes to **management**, the metaverse bolsters the ability of ports to handle critical data and information efficiently and securely. Technologies such as blockchain, integrated into the metaverse environment, guarantee transparency in data management and improve traceability throughout the logistics chain. Likewise, the metaverse can be used to monitor port infrastructure, allowing remote monitoring of equipment in real time and early detection of failures, which reduces maintenance costs and improves operational availability.

From a **collaborative** perspective, the metaverse fosters a more fluid and effective interaction between the various actors in the port ecosystem. The ability to connect different stakeholders in an immersive, three-dimensional environment allows for real-time coordination of efforts, sharing critical information, and improving collaborative decision-making. This aspect is particularly relevant in emergency management or joint strategic planning, where agile and efficient communication is essential.

The metaverse's impact on **sustainability** is also significant. By optimizing logistics routes and resource utilization, this technology contributes to the reduction of carbon emissions and promotes sustainable practices in ports. Real-time simulations and digital planning also make it possible to assess and mitigate environmental impacts before project execution, aligning port operations with the Sustainable Development Goals (SDGs).

However, the implementation of the metaverse faces challenges that must be addressed to ensure its success. Among the main obstacles identified are limited interoperability between technology systems, lack of common standards, and high upfront costs associated with infrastructure and staff training. In addition, concerns around cybersecurity and resistance to organizational change represent critical barriers to the adoption of this technology. It is therefore essential to develop a strategic framework that addresses these constraints, encouraging cooperation between port authorities, investment in modern infrastructure and continuous training of staff.

The conclusions also underscore the need to establish public policies that promote the adoption of the metaverse in ports. These policies should include financial incentives, training programs, and the creation of standards and protocols that facilitate technological interoperability. Collaboration between sectors, such as ports and aeronautics, is also presented as a key strategy to take advantage of experiences and knowledge in the implementation of advanced digital technologies.

In short, the metaverse has the potential to transform ports into "metaports," integrating innovation, sustainability, and collaboration into a digitized environment. While the benefits include significant improvements in operational efficiency, environmental sustainability, and global competitiveness, its implementation requires strategic vision, sustained investment, and a collaborative approach among all actors involved. By overcoming current challenges, the metaverse can consolidate itself as a key tool for the future of Spanish ports, positioning them as international benchmarks in the era of digitalization.

The **RQ4 research question, "How will the application of the ETS affect European ports, reconfiguring the economic, operational and environmental dynamics of the maritime sector?"**, has been approached with a comprehensive approach that reveals both the challenges and opportunities that this system poses for European ports. The ETS emerges as a central tool for the transition towards climate neutrality, with profound implications for the competitiveness, sustainability and operability of the port sector.

In economic terms, the implementation of the ETS generates significant costs for shipping companies, which can negatively impact the competitiveness of European ports against hubs not subject to these regulations, such as some African or British ports. This phenomenon of "carbon leakage" could result in a redirection of maritime traffic to regions with less strict regulations, weakening the position of European ports in global logistics chains. However, the ETS also creates financial incentives that can stimulate investment in green technologies, encouraging the development of alternative fuels and the modernisation of port infrastructure.

From an operational perspective, a reconfiguration of shipping lanes and logistics patterns is expected as shipping companies adjust their strategies to minimize costs derived from emissions. Although this impact will not be immediate due to the gradual implementation of the ETS (40% of emissions in 2024, 70% in 2025, and 100% in 2026), it is essential to anticipate these changes in order to develop effective mitigation measures. One possible solution would be to channel the funds raised through the ETS towards projects that promote sustainability in the most affected ports, such as the electrification of docks and the adoption of energy-efficient technologies.

In terms of sustainability, the ETS can be a catalyst to accelerate the maritime sector's transition towards more environmentally friendly practices. The economic pressure that this system imposes can incentivize the adoption of clean technologies and the reduction of emissions throughout the logistics chain. However, the positive environmental impact of the ETS could be compromised if there is an increase in land transport as a result of a reduction in maritime operations, especially on short sea shipping routes. This phenomenon underscores the need for a balanced approach that does not shift emissions to other, more polluting modes of transport.

A key takeaway from this analysis is the importance of using the funds raised by the ETS strategically. In addition to encouraging technological innovation, these resources should be used to support ports that face losses of competitiveness due to the implementation of the system. This could include tax incentives, subsidies for the transition to sustainable fuels and the modernization of infrastructure. It would also be essential to adjust the legislative criteria of the ETS to include relevant competing ports beyond the current geographical proximity thresholds, such as certain African or British ports that pose a direct threat in terms of carbon leakage.

At the regulatory level, the ETS highlights the need for a harmonised framework that facilitates its integration with global maritime policies. Without proper coordination, there is a risk of fragmenting the regulatory landscape, which could hinder the effective implementation of the system and increase inequalities between regions. In this sense, the concept of "transparent port" requires a revision to include competing ports based on their strategic relevance and not only their geographical proximity.

Finally, the socioeconomic impact of the ETS should not be underestimated. Changes in maritime traffic and logistics routes could affect local communities that depend on ports for their economic livelihoods. It is therefore essential to balance environmental objectives with economic resilience and social equity, ensuring that the benefits of this system are distributed fairly.

In conclusion, the ETS represents a transformative challenge for European ports, but also an opportunity to lead the transition towards a more sustainable and competitive maritime sector. Although the system poses initial costs and risks, its correct implementation can position European ports as global benchmarks in the fight against climate change. To this end, it is essential to develop strategies that minimise negative impacts, seize opportunities for innovation and ensure a just and balanced transition. By overcoming these challenges, European ports will not only contribute to the objectives of the European Green Deal, but will also strengthen their resilience in an increasingly dynamic and demanding global logistics environment.

The RQ5 research question **, "How can Bayesian networks help assess the sustainability of the marine renewable energy sector in Spanish ports, enabling better strategic decision-making?"**, has been answered through an innovative approach that combines probabilistic analysis with specific sustainability indicators. This study demonstrates that Bayesian networks are key tools to address the complexity and uncertainty inherent in strategic planning in the context of sustainable development.

Firstly, Bayesian networks have made it possible to identify the most decisive indicators for the sustainable development of the marine renewable energy sector in Spanish ports. Among these, the **evolution of economic investments** and **efforts in environmental characterization** stand out, which represent critical factors both to guarantee economic growth and to minimize the environmental impact of activities related to this sector. These variables offer a solid basis for prioritizing resources and designing strategies that promote a balance between environmental, economic and social sustainability.

The Bayesian model developed provides a comprehensive view of the interrelationships between different indicators, allowing both the analysis of direct dependencies and the inference of indirect relationships. This ability to model complex systems is particularly useful in a port environment, where economic, social, and environmental factors are intrinsically interconnected. For example, the analysis shows how increased investment in port infrastructure can facilitate the adoption of renewable energy technologies, while proper environmental characterization ensures that these investments are compatible with the conservation of marine ecosystems.

A relevant finding is the importance of **occupational safety** in the development of the sector. The rate of occupational accidents was identified as a key indicator, underscoring the need to implement measures that guarantee the safety of workers. This approach not only contributes to social well-being, but also strengthens operational sustainability and reduces risks associated with project disruptions. This reinforces the idea that a successful energy transition must consider both technical and human aspects.

In strategic terms, this study highlights the usefulness of the Bayesian model as a support tool for decision-making. By quantifying the relationships between variables, the model makes it possible to predict the impacts of different investment and regulation strategies, optimizing the use of available resources. In addition, this methodology provides a flexible platform to incorporate dynamic data and assess the impact of specific policies and actions over time.

However, the analysis also reveals significant challenges, such as the lack of homogeneity in the data and the need to improve coordination between port authorities. The integration of an open data repository could address this limitation, allowing for the collection and sharing of indicators in real time. This would not only improve the quality of analysis, but also foster collaboration and transparency in port management.

From an environmental perspective, Bayesian grids have proven to be especially useful in ensuring that offshore renewable energy projects are compatible with sustainability goals. By integrating environmental considerations into strategic planning, ports can minimize their ecological footprint while maximizing economic and social benefits. This approach also supports the fulfilment of climate commitments set out by the European Union, such as the European Green Deal and the "Fit for 55" programme.

In conclusion, the use of Bayesian networks to assess the sustainability of the marine renewable energy sector in Spanish ports offers an innovative and practical methodology that significantly improves strategic decision-making. By providing a comprehensive view of the interdependencies between key factors, this approach allows port managers to identify critical areas of intervention, optimize resources, and ensure sustainable development. This model not only reinforces the role of ports in the transition to a low-carbon economy, but also positions Spanish ports as leaders in the Blue Economy, contributing to the resilience and sustainability of coastal regions in the global context.

10.1. Limitations

Throughout this research, limitations have been identified that have influenced the development and scope of the study. These limitations can be grouped into three major areas: methodological, contextual and technological.

One of the main methodological challenges has been the reliance on data available from secondary sources. Especially in emerging sectors of the Blue Economy, the heterogeneity in the quality and availability of data between the different Port Authorities has led to an effort in the standardisation and uniformity of databases for analysis. While some ports have made progress in the collection and digitization of information, others still have lags in the documentation and transparency of their data.

The study has focused on the Spanish and European port context, which could limit the extrapolation of the results to other global port systems with different regulatory, economic and technological frameworks. Local conditions, such as the governance structure and the degree of digitalisation, may influence the applicability of the findings in other regions.

In addition, some of the phenomena analysed are subject to legislative and policy changes. For example, the implementation of the Emissions Trading System (ETS) and the development of offshore renewables depend on constantly evolving regulations, which could change outcomes in the medium and long term.

Port digitalization and the incorporation of emerging technologies, such as virtual ecosystems and digital twins, are at an early stage of development and adoption. While the research results suggest great potential to improve efficiency and sustainability in ports, the lack of standardization and barriers to technological adoption may delay its large-scale implementation. In this sense, it is highlighted that this research has been a pioneer in the analysis of virtual universes in the port context, which represents both a strength and a possible limitation due to the scarcity of previous studies with which to contrast the findings.

10.2. Future lines of research

Given the dynamic nature of the Blue Economy and the digital transformation in ports, several areas of research are identified that can broaden and deepen the results obtained in this study.

One of the main pending challenges is to extend the Blue Economy evaluation model to other international contexts. The application of the model to regions with different port structures and legislation would validate its robustness and improve its overall applicability. In addition, it is crucial to analyse the evolution of emerging sectors in terms of support and financing policies, which could provide a clearer view on the most effective strategies to promote sustainability in ports.

As the Emissions Trading System (ETS) continues to evolve, complementary alternatives need to be explored to mitigate its economic impact on ports, allowing for the evaluation of more efficient and less costly options for the decarbonization of maritime and port transport.

The use of Bayesian nets has proven to be an effective methodology for assessing sustainability in the offshore renewable energy sector. As a line of future research, it is proposed to apply this methodology to other fields of port exploitation. This will allow the development of predictive models that guide informed decision-making in different sectors.

The role of policy and governance in the transition to more sustainable ports is a crucial line of research. Carrying out an analysis of political and economic strategies to balance sustainability with competitiveness in ports, thus ensuring that environmental regulations do not generate operational disadvantages compared to ports outside the EU. In addition, it is relevant to deepen collaborative governance between ports and explore cooperation mechanisms for the implementation of the Blue Economy and the energy transition.

In conclusion, these future lines of research offer a wide range of possibilities to continue advancing in the transition towards a more sustainable, digitalised and resilient port model in the face of the challenges of climate change and the globalisation of maritime trade.

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