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GREEN PRACTICES FOR REDUCING EMISSIONS IN PORT SERVICES: EVIDENCE FROM A PILOT STUDY

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Abstract: This paper focuses on operational practices that can reduce emissions in port services, especially within nautical operations. By using theoretical and empirical approaches, the research adopts a mixed-method design that integrates desk research, stakeholder surveys, and case study analysis. The study identifies and classifies twelve optimal operational practices through an innovative multidimensional framework, which considers environmental, economic, social, technical, and institutional dimensions. The findings highlight the relevant importance of promoting behavioural changes among port service operators to ensure the effective adoption of sustainable practices. To this end, the study highlights the need to develop specific and targeted training programs. They aim to raise public awareness of environmental issues and improve personnel operational efficiency. Such programs are identified as crucial elements to facilitate the transition towards more sustainable and efficient operating models. This fosters a long-term positive impact on both environmental performance and the entire maritime logistics chain. The research concludes by recommending how ports can incorporate these practices into training programs that promote sustainable behaviour and improve operational decision-making.

Keywords: *Green Port Practices, Sustainable Port Operations, Behavioural Change in Nautical Services, Stakeholder Engagement, Data-driven management, Mixed-methods.*

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1. Introduction

Ports serve as crucial nodes within global supply chains, highlighting international trade and making a substantial contribution to economic development and regional competitiveness. At the same time, their role in maritime logistics positions them among prominent contributors to environmental pollution, primarily through substantial emissions, resource depletion, and extensive energy consumption [1,2]. Maritime operations are a significant source of pollutant emissions. These operations include: a. technical-nautical services, such as pilotage, towing, and mooring; b. onboard activities carried out on various types of vessels, including cruise ships, vehicle carriers, container ships, general cargo ships, and oil tankers. These include carbon dioxide (CO_2), nitrogen oxides (NO_x), sulphur oxides (SO_x), particulate matter (PM), and volatile organic compounds (VOCs).

These emissions adversely affect urban air quality, exacerbate climate change, and compromise public health [2,3].

International and regional regulatory frameworks have intensified in response to growing environmental concerns and increasing attention to sustainability issues. Consequently, the International Maritime Organization (IMO) has set stringent emission standards. It did this through the MARPOL Convention. Meanwhile, the European Union (EU) introduced the Green Deal. The goal is to achieve global climate neutrality by 2050. These regulatory imperatives are pushing ports to adopt comprehensive environmental management practices. This also strengthens their strategic role in advancing global sustainability goals [4,5]. As a result, port managers have adopted global "green port" initiatives, which can be explained as an integrated approach that aligns environmental goals with technological innovations, operational optimisation, social responsibility, economic performance and institutional collaboration [1,6]. However, the successful implementation of such practices remains challenging. Technological advancements alone are insufficient; lasting environmental outcomes require behavioural change, institutional support and active stakeholder engagement [7,8].

Port authorities and stakeholders frequently encounter difficulties identifying, prioritising, and implementing effective sustainability measures due to the diverse range of available practices, varying regulatory landscapes, operational limitations, and the challenge of securing widespread stakeholder acceptance [8,9].

This study addresses these critical issues by systematically identifying, evaluating, and prioritising sustainable practices explicitly designed to reduce harmful emissions within port operations, focusing especially on technical-nautical services. The research identifies twelve effective practices for achieving substantial emission reductions and improving operational sustainability by employing a mixed-method research design that combines qualitative expert consultations with quantitative stakeholder evaluations. Furthermore, the study applies to an original analytical framework. This includes environmental, economic, social, technical and institutional dimensions. The adopted approach allows for a comprehensive assessment of the sustainability practices examined. The paper aims to identify and rigorously assess practices capable of significantly reducing emissions in technical-nautical port services. This approach validates a structured analytical framework. This allows for assessing practices from multiple critical perspectives and translating the results into actionable management and training recommendations. The results obtained aim to promote sustainable operational behaviours. Furthermore, they aim to improve stakeholder engagement and ultimately support the transition of the maritime sector towards sustainability.

This study contributes to the discourse on sustainable port operations by offering an empirically validated framework for evaluating emission-reduction practices in technical-nautical services. Unlike previous studies, which often focus on infrastructure-based interventions or high-level policy strategies, this research emphasises operational and behavioural practices that can be directly implemented by port service providers [1,2,7,9]. Based on stakeholder evaluations and a multidimensional analytical framework, the paper identifies twelve high-impact practices, ranked according to sustainability-related evaluation parameters. Our results help ports develop training strategies that encourage daily sustainable behaviours among operators. Beyond operational value, the study also contributes new perspectives to current academic and managerial debates.

The next sections of the paper include a comprehensive review of the theoretical framework on port sustainability. A detailed account of the methodology follows. An analysis of the results is then presented. Finally, the main theoretical and managerial implications are discussed. In particular, Section 2 outlines the conceptual basis. It focuses on sustainable port operations, digital transformation and behavioural training. Section 3 describes the mixed-methods research design adopted in the study. The data collection process and the development of the analytical framework are explained. Section 4 presents the evaluation and validation of the selected sustainability practices. Section 5 discusses the main findings, considering the existing literature. The practical and theoretical relevance of the results obtained is highlighted. Finally, Section 6 concludes the paper, summarising the contributions made and proposing paths for future research.

2. Theoretical background

2.1 Sustainability and Emission Reduction in Port Operations

Building on their critical role in global trade, ports are facing increasing scrutiny due to their significant environmental impact, particularly in terms of air emissions and energy consumption [10]. To address these challenges, international regulatory frameworks have introduced stringent environmental standards.

Considering intensifying regulatory frameworks and growing expectations for environmental sustainability, ports have increasingly adopted the "green port" paradigm. This approach promotes integrated strategies. These include energy efficiency measures, low-emission technologies and digital tools tailored to operational needs [1,6,11,12]. In this context, several specific practices have emerged that offer concrete ways to improve the sustainability of port operations. Among the most relevant practices is the adoption of alternative fuels, such as liquefied natural gas (LNG), hydrogen and biofuels. Another solution is the implementation of shore-side power systems (OPS). These systems allow ships to switch off their auxiliary engines during docking, significantly reducing emissions in the port environment [7,8]. In addition, advanced sensor technologies and continuous emission monitoring systems have been widely implemented. These tools provide ports with real-time data, which is useful for effectively monitoring and managing environmental performance [9]. Integrated environmental practices help port authorities meet regulatory compliance requirements. At the same time, they contribute to reducing operating costs through increased energy efficiency. Finally, they attract eco-conscious stakeholders, strengthening the competitive positioning of ports [6,13].

Empirical evidence demonstrates the significant benefits of proactive green port strategies. These strategies generate measurable environmental and economic benefits. One of the most significant examples is the Port of Los Angeles, where Alternative Maritime Power (AMP) has been successfully implemented. The system provides a large power grid to berthed ships, drastically reducing local emissions and fuel consumption [14]. Another example is the Port of Rotterdam, which is recognised worldwide for its sustainable practices. The port has invested in renewable energy infrastructure, energy-efficient technologies, advanced waste treatment systems and comprehensive emission monitoring. These measures have led to a significant reduction in emissions. They have also aligned the port's operations with broader climate goals, setting a global benchmark for port sustainability [15]. Moreover, academic analyses confirm that ports implementing such sustainability initiatives achieve regulatory compliance and improve their market attractiveness, customer loyalty, and overall stakeholder satisfaction by aligning themselves clearly with global sustainability trends [13,16]. Thus, embracing green port strategies is becoming a strategic imperative for modern ports seeking both environmental sustainability and competitive advantage within the global maritime industry.

2.2 Digital Transformation and Innovation in Port Management

In recent years, the port industry has increasingly turned to technological innovation. This choice is a strategic response to the growing pressure to improve operational efficiency, environmental sustainability and supply chain resilience [17,18,19]. The evolution towards intelligent port systems is based on the principles of Industry 4.0. This model values digital connectivity, automation and the use of data in industrial processes [20]. The digital transformation of port ecosystems requires the integration of different technologies. These include the Internet of Things (IoT), artificial intelligence (AI), big data analytics and Cyber-Physical Systems (CPS). These technologies enable real-time monitoring, predictive decision-making and autonomous operations throughout the port environment [21,22,23].

A key component of smart port architecture is the IoT infrastructure. It connects physical port assets—such as cranes, containers, vessels, vehicles, and monitoring equipment—through wireless networks and arrays of sensors. These devices collect and transmit real-time data on location, movement, condition, and performance, thus creating a digital layer over the physical environment that supports seamless information flow and operational control [21,24]. IoT-based platforms facilitate machine-to-machine communication while also supporting advanced tracking and monitoring for emissions and energy usage [21].

Artificial intelligence in smart ports has a role that goes beyond automation. It contributes to predictive analytics and decision-making in all operational scenarios. AI-based tools are used to predict ship arrivals. They also help optimise the use of resources [21,23]. When combined with big data analytics, AI enables the extraction of actionable insights from large amounts of data. These technologies help port operators respond flexibly. They can adapt to changes in cargo volume, weather conditions, or workforce availability [25,26].

The integration of CPS adds a new dimension to port digitalisation [27]. CPS connect the physical and digital worlds. They enable equipment to be automated based on real-time environmental feedback. This reduces human error and improves system resilience. These systems include integrated sensors, actuators and control mechanisms. They can make decisions autonomously. They form the technological backbone for self-driving vehicles and remote-controlled cranes. They also include aquadromes that monitor fuel consumption, propulsion systems and mooring operations [21,24,25].

Terminal Operating Systems (TOS), Enterprise Resource Planning (ERP), and Supervisory Control and Data Acquisition (SCADA) systems are necessary to manage the data-driven operations of a smart port. These systems can be configured to collect environmental performance data during vessel assistance and integrate it with broader port sustainable metrics [21,28]. By connecting these software environments to automated equipment and IoT platforms, ports achieve end-to-end integration. This process extends from the arrival of ships to the movement of cargo, to the coordination of inland transport.

Emerging smart port strategies also include the implementation of digital twin technologies. These virtual twins simulate and visualise port operations in real time. Digital twin platforms allow operators to test scenarios in a virtual environment. They can simulate, for example, traffic rerouting, crane scheduling or climate impact mitigation. This reduces risks and enables more informed decision-making [21].

The implementation of these technologies yields measurable improvements. Studies show that smart port deployments lead to reduced vessel turnaround times, lower emissions, and higher equipment utilisation rates, while improving labour safety and customer responsiveness [26, 29]. For example, ports like Rotterdam, Hamburg, and Quebec have pioneered integrated systems combining AI, IoT, and automation, positioning themselves as benchmarks in smart logistics and green port innovation [21, 30].

However, these advances present challenges. The cost of digital infrastructure, cybersecurity vulnerabilities, and institutional resistance can hinder implementation.

This is especially true for ports located in developing regions or operating with fragmented governance systems [29,31]. The need to reskill the workforce, manage data, and foster interorganizational collaboration increases the complexity of transitions to smart ports [21,28]. Smart ports represent a structural change in the way they operate.

They also deliver sustainable value along maritime supply chains. By integrating intelligence and connectivity into infrastructure and operations, smart ports create the foundation for sustainable, resilient, and customer-centric maritime logistics.

2.3 Behavioural Training and Stakeholder Engagement for Sustainable Practices

Even with new technologies, the success of sustainable practices in ports depends on how well human operators understand and apply them [8]. Maritime logistics continue to rely on human intervention, particularly in technical-nautical services where tasks such as pilotage, tug operations, and mooring require precision and environmental awareness. Recent studies highlight that technology alone is not sufficient to ensure strong environmental performance; instead, it requires targeted behavioural interventions and structured professional training programs explicitly tailored to maritime personnel [8,6]. Human factors such as motivation, knowledge, skills, and continuous reinforcement significantly play a critical role in embedding sustainability strategies into daily operations. As a result, enhancing the environmental competencies of pilots and port managers through comprehensive training frameworks has become a key priority in sustainability-oriented port governance [6].

Effective methods include scenario-based simulation, Virtual Reality (VR) environments, real-time feedback from Port Community Systems (PCS), and continuous professional development programs [7,8]. Scenario-based simulation training allows personnel to experience realistic operational situations in controlled environments, enhancing their ability to respond effectively under real-world conditions and improving environmental performance through reduced inefficiencies and optimised behaviours [8]. Virtual reality training is very useful in complex maritime operations. It can simulate piloting manoeuvres and tugboat operations. These simulations take place in different weather and traffic conditions. They offer risk-free experiential learning. They also promote greater situational adaptability [8]. Furthermore, real-time feedback systems help operators better understand the environmental impact of their actions. These systems are based on data collected by PCS platforms. They make the immediate effect of adopted behaviours evident. This encourages corrective actions such as optimised route planning. They also push to reduce engine idling periods and to perform more energy-efficient manoeuvres [8,16]. Pilot studies show concrete results. When digital training is combined with measurable environmental indicators, operators become more aware. They practice sustainable behaviours more consistently. This leads to tangible reductions in emissions [6,8].

In addition to training, active stakeholder involvement is important. This is an essential factor in successfully implementing sustainable port practices. Stakeholders include operational staff, management and external parties. These include shipping companies, logistics providers and regulatory agencies. Their involvement promotes shared responsibility. It also fosters a sense of collective ownership of sustainability initiatives [6,17]. Participatory decision-making brings many benefits. When stakeholders help design, implement and evaluate environmental strategies, acceptance is higher. Coordination improves and environmental results last longer [1,6]. For example, port authorities that involve stakeholders from the beginning achieve several benefits. There is better alignment of organisational goals. Implementation is smoother. Operational compliance is also higher [1]. Empirical studies confirm this. Stakeholder involvement and transparent communication reduce resistance to change. This facilitates easier transitions to sustainable operational practices [17]. Additionally, actively involving port workers and maritime professionals in continuously improving and refining environmental procedures enhances practical effectiveness and reinforces an organisational culture committed to environmental responsibility [6,17].

Comprehensive human resource development—including structured education, hands-on training, and inclusive stakeholder engagement—is essential for delivering lasting emission reductions and maintaining environmental compliance. When paired with technology, these behavioural and cultural shifts strengthen the maritime sector's ability to meet sustainability and performance goals [28].

3. Materials and Methods

3.1 Research Design

In this study we used a mix of qualitative and quantitative methods, grounded in case study analysis, to explore how sustainability strategies work in practice across different ports. The choice to use a mixed approach arises from a necessity. It was important to understand the issues comprehensively. For this reason, qualitative exploration was balanced with statistical analysis based on validated data [33,34,35]. The qualitative phase included two main activities. The first was the literature review, while the second was the selection of case studies. This phase allowed an in-depth exploration of the operational dynamics that fostered the understanding of the context. It also helped to identify the best practices to reduce emissions and improve sustainability in technical-nautical services. The qualitative data collected offered important insights. They clarified the operational challenges and highlighted the stakeholders' perspectives. They also showed sustainability opportunities specific to each context [36,37]. The quantitative phase involved the use of structured questionnaires. These were administered by stakeholders. The questionnaire was used to evaluate two aspects. The first was the perceived effectiveness of sustainability practices, and the second was their operational feasibility. The practices considered emerged from the previous literature review. By combining the two approaches, the research obtained more solid results. It validated the data and generalised the results in different port contexts. This increased the robustness and reliability of the conclusions [38,39]. The quantitative data confirmed qualitative insight and offered an evidence-based assessment of each practice's relevance, feasibility, and impact across different port environments.

A multiple case study approach was adopted to reinforce the study's empirical foundation further. The research included a subsequent operational phase focused on developing and distributing a "Case Study Identification Sheet" to key stakeholders in the port sector. The primary objective of this initiative was to collect case studies based on the practical application of the 12 best practices previously identified. The design of the sheet was grounded in a review of relevant academic and professional literature to ensure construct validity and clarity.

The administration of the sheet produced dual outcomes: first, it facilitated the identification of benchmark ports; second, it enabled an in-depth analysis of the operational practices adopted in these contexts. This approach proved particularly effective in examining complex phenomena in real-world settings, where multiple operational variables and contextual factors significantly influence outcomes [40,41,42].

By triangulating these data with previous phases of analysis, the study was able to strengthen both the theoretical constructions and the practical implications. By analysing port operations characterised by exemplary sustainability practices, the research validated theoretical propositions and added value in terms of practical applicability. The case studies provided rich and contextualised narratives. These narratives supported both qualitative exploration and quantitative evaluation. The methodological framework was designed with three main objectives. The first objective is to systematically identify and evaluate best practices. These practices address the reduction of harmful emissions in technical-nautical services. The second objective is to empirically validate these practices.

This was done through active stakeholder involvement. The objective was to ensure their practical applicability. It was also important to ensure broad acceptance in the maritime sector. The third objective is to exploit the empirical findings. These findings should be translated into operational guidelines. Furthermore, they should generate actionable policy recommendations. The final objective is to improve sustainable performance. It is also important to strengthen the environmental management of port operations.

The final objective was to identify several case studies from different countries. The aim was to provide a differentiated perspective on the application of best practices. Cases from Italy, Portugal, Spain, Belgium and Turkey were selected. This choice reflects the geographical and operational diversity of European ports. Furthermore, it reflects the availability of reliable data provided by stakeholders active in those countries. Initially, ports from other regions were also considered. However, some did not provide sufficient data, and others refused to participate in the study. For this reason, they were not included in the final analysis. This practical limitation does not reduce the validity of the selected ports. They nevertheless represent a variety of sustainability challenges. They also offer examples of different approaches to governance.

3.2 Data collection

The data collection process was divided into two main phases. The first phase involved desk research; the second phase involved field analysis. Both phases aimed to collect complete and reliable information on sustainable operational practices in ports. Desk research was essential to build a solid theoretical base. During this phase, a systematic review was conducted. Academic articles, industry association reports and relevant institutional documents were analysed. This analysis allowed us to identify existing or proposed sustainable practices. These practices were classified according to their potential for transferability and applicability in the port context. As a result, an initial list of 13 key practices was created, categorised into three main thematic clusters: emissions reduction, operational efficiency improvement, and professional development and engagement.

The three clusters represent macro-categories of practices applicable in ports to reduce the environmental impact of towage and pilotage operations (Figure 1). Each cluster reflects a specific intervention perspective. Analysing each perspective is useful for analysing, classifying and comparing initiatives according to their nature and objectives. In particular:

- Cluster 1 - Emission reduction practices (strategic aspects): This cluster comprises practices explicitly aimed at reducing pollutant emissions. It relies on technological upgrades, maintenance strategies and management measures. It includes actions aimed at changing the technical characteristics of vessels or organisational behaviour in order to limit emissions of greenhouse gases and air pollutants.
- Cluster 2 - Operational efficiency enhancements (operational aspects): This cluster focuses on practices that improve operational efficiency by optimising the use of resources (e.g. fuel, time, labour). Although not primarily designed to reduce emissions, these actions achieve environmental benefits as a derivative of increased efficiency, e.g. through route optimisation or smoother manoeuvring processes.
- Cluster 3 - Engagement and professional development (educational aspects): This cluster brings together the supporting actions, such as training, awareness-raising and monitoring. These actions create the conditions for the successful implementation of environmental practices. It includes non-material initiatives that foster cultural change and continuous monitoring, promoting a more environmentally aware system.

Figure 1 - Main characteristics of the three identified clusters

CLUSTER	FOCUS	KEY ACTIONS	ENVIRONMENTAL CONTRIBUTION
1 - Emission reduction practices (strategic aspects)	Direct reduction of pollutant emissions	• Use of alternative fuels • Engine maintenance • Green propulsion systems • Environmental reporting	**Primary objective**: lower greenhouse gas and pollutant emissions through technology and management
2 - Operational efficiency enhancements (operational aspects)	Optimization of resource use	• Route and speed optimization • Reduced engine idling • Simulation tools for maneuvers	**Indirect impact**: lower emissions as a result of increased operational efficiency
3 - Engagement and professional development (educational aspects)	Capacity building and cultural change	• Staff training • Awareness campaigns • Emissions monitoring	**Enabling factor**: supports the effective and sustained implementation of environmental measures

These clusters served as the reference framework for the subsequent analysis, establishing a strong theoretical basis upon which to build. The next step was field analysis. In this phase, a questionnaire was administered to port operators. The main objective was to validate the practices identified during the documentary research. In addition, new proposals were collected directly from professionals in the sector. This step was essential to connect the research to the operational reality. The empirical feedback allowed us to strengthen and refine theoretical knowledge. The active participation of the interviewees was essential. They answered the questionnaire and involved other local port operators. This ensured broader and more representative data collection. Subjects from different operational sectors were included. Among them: maritime pilots, tug operators, mooring personnel, logistics service providers and representatives of port management. This allowed us to obtain a rich and varied data set. The data collected covers multiple aspects of port operations.

The survey involved a group of 40 stakeholders. All of them were actively engaged in daily technical-nautical operations. The interviewees evaluated each practice using a five-point Likert scale. The score ranged from 1 (low effectiveness) to 5 (high effectiveness). The practices were analysed according to different dimensions. Among them are the potential for emission reduction, economic feasibility, ease of integration into daily operations, and overall impact on sustainability. This method allowed us to clearly understand how the operators perceived the proposed practices. The data collected was very useful for the next phase of analysis. Methodological triangulation was used to increase the validity and reliability of the results [32,39]. This strategy involved cross-checking the data. The data came from both the literature review and structured quantitative surveys. Triangulation improved the quality of the data set. It reduced possible biases and confirmed the consistency of the results between independent sources. In this way, the data collection identified relevant and feasible sustainability practices. It also strengthened the empirical credibility of the analytical framework and the study findings.

3.3 Case Study Selection

The selection of case studies followed a rigorous process. The process was strategically designed. It was guided by criteria consistent with the research objectives. These criteria aimed to identify successful practices. In particular, effective practices in reducing emissions in ports. The focus was on ports adopting advanced environmental practices. Ports that have received recognition in the maritime sector [23,34,35] were also considered. This approach ensured the selection of innovative cases. Each port included represented a relevant example of sustainable operations.

The geographical scope was limited to the European maritime sector. This choice was made intentionally. The aim was to ensure regulatory coherence between cases. Furthermore, it was intended to facilitate the comparability of the results. This regional focus strengthened the validity of the research. It also allowed for more generalisable results. The results are better applied to contexts with similar legal, institutional and operational frameworks [15,18,20].

An additional selection criterion concerned the adoption of environmental measures. These measures had to be integrated into specific technical-nautical services. The services considered included pilotage, tugboat operations and mooring activities. These services are relevant for their contribution to port emissions [2,6,13]. This focus allowed for a detailed assessment of the practices. The practices directly influence the emission levels in critical operational activities. Compliance with regulatory standards constituted another essential selection filter; case studies were selected among ports demonstrating stringent adherence to international environmental regulations [1,4,29].

The study established a robust empirical basis for evaluating sustainability-focused operation practices' implementation, performance and transferability through this structured, multidimensional selection framework. This strategic approach ensured that the findings reflected proven success cases and yielded actionable, generalisable insights applicable to other ports operating under comparable environmental and governance conditions.

3.4 Analytical framework

The analysis and selection of the identified practices were guided by an analytical framework. This framework is based on ten evaluation parameters, divided into five main perspectives: environmental, economic, social, technical and institutional (Figure 2). The multidimensional framework was designed to ensure a comprehensive understanding of the proposed practices' effectiveness, relevance and impact. Furthermore, it promotes a balance between operational needs, sustainability and innovation.

Figure 2 – The ten evaluation parameters

PERSPECTIVE	ID	PARAMETER	DESCRIPTION
Environmental perspective (A)	A1	**Reduction of greenhouse gas emissions**	Measures the effectiveness of the practice in reducing the emission of CO_2, NOx, and other pollutants into the atmosphere
	A2	**Preservation of natural resources**	Assesses the impact of the practice on the sustainable use of resources such as fuels, water, and other natural raw materials
Economic perspective (B)	B1	**Cost of implementation**	Estimates the initial cost required to adopt the practice, including equipment, training, and installations
	B2	**Long-term operational savings**	Assesses the ability of the practice to reduce operating costs over time, such as savings on fuels or maintenance
Social perspective (C)	C1	**Acceptability among workers and the community**	Measures the degree of acceptance and acceptance of the practice by pilots, port personnel, and the local community
	C2	**Improved health and safety**	Assesses the impact of the practice on reducing health and safety risks to workers and the nearby population
Technical perspective (D)	D1	**Ease of integration with legacy technologies**	Assesses how easy it is to integrate the practice with current port infrastructure and technology.
	D2	**Maintainability and reliability**	Measures the technical robustness and ease of maintenance of the adopted solution, reducing downtime
Perspective of government institutions and authorities (E)	E1	**Compliance with environmental regulations**	Assesses whether the practice meets local, national or international regulatory requirements.
	E2	**Support from government institutions**	Measures the degree of promotion, incentive or facilitation offered by authorities for adopting the practice

The environmental perspective focused on the ecological impact of practices. Their potential to reduce the ecological footprint, limit greenhouse gas emissions and promote sustainable resource management was assessed. Solutions such as continuous monitoring of emissions and the use of alternative fuels, such as biofuels, are examples of practices that reduce air pollution and improve energy efficiency.

The economic perspective analysed the financial benefits of adopting such practices. In particular, the reduction of operating costs, the improvement of efficiency and the long-term return on investment were examined. Examples of practices in this perspective include the optimisation of shipping routes and the reduction of vessel downtime. These solutions reduce costs and improve operational sustainability.

The social perspective considered the well-being of port workers. Safety, health, quality of working life and the level of acceptance of the proposed practices were assessed. Key practices included worker involvement in decision-making processes and continuous training. These interventions aim to increase motivation and productivity while reducing operational risks.

The technical perspective examined the feasibility and technological innovation of the practices. Their ability to improve port operations and integrate with existing infrastructure was assessed. Examples of practices in this perspective include real-time monitoring and digital simulation of port manoeuvres. These solutions improve operational efficiency and reduce risks.

The institutional and governmental perspective assessed the alignment of practices with local and international regulations. It also considered the support of government authorities for their implementation. Examples of practices in this perspective are those that encourage collaboration between ports to exchange environmental information. Other practices that comply with international regulations also meet the governance objectives of transparency.

Each perspective included specific parameters. These parameters were used to measure in detail the impact of the solutions adopted. They provide a structured framework to compare alternative practices and ensure their effectiveness. The ten evaluation parameters are: reduction of greenhouse gas emissions and conservation of natural resources for the environmental perspective; implementation costs and long-term operational savings for the economic perspective; acceptability among workers and the community and improvement of health and safety for the social perspective; ease of integration with existing technologies, maintainability and reliability for the technical perspective; compliance with environmental regulations and institutional support for the institutional perspective. This evaluation system allowed us to select 12 definitive practices. It also allowed us to evaluate their concrete applicability and scalability in the port context.

The proposed model contributes to the evolution of port governance by promoting data-driven, integrated, and practical sustainability solutions for the ports of the future.

3.5 Stakeholder engagement

Stakeholder involvement is crucial for the success of research. This is especially true in complex operational contexts, such as ports. Their participation improves the methodological soundness and reliability of the results. It also ensures that the proposed solutions are aligned with the practical needs of port managers and operators. Active stakeholder involvement makes the results more concrete and relevant. It allows to respond directly to the needs of the sector. The integration of different professional skills enriches the research. It improves the depth of the analysis and makes the selection of sustainable practices more effective. This approach leads to operational, concrete and adaptable solutions over time.

In this research, data collection was conducted through a targeted survey. The survey was distributed between September 17 and October 4, 2024. Stakeholders actively involved in technical, nautical and port management operations were involved. These included: maritime pilots, tugboat operators, mooring specialists, logistics providers and port management representatives. With this approach, the study covered all key aspects of port operations. Each stakeholder group offered valuable input. The responses were based on first-hand experience and professional expertise. For example, maritime pilots focused on practices related to operational safety. Logistics providers, on the other hand, emphasized strategies to improve efficiency and reduce costs.

The study deliberately involved a broad spectrum of stakeholders. In this way, it effectively captured different operational roles and points of view. This approach significantly improves the credibility of the findings. It also broadens their applicability in different port contexts. The structured Likert-scale format utilised in the questionnaire enabled the gathering of measurable data, facilitating a systematic evaluation and comparative analysis of the proposed sustainability practices. This quantitative methodology also helped minimise subjective biases, strengthening the overall objectivity of the study.

To further validate the results, a follow-up phase was launched in January 2025. In this phase, a "Case Study Identification Sheet" was distributed. The questionnaire was sent to the main stakeholders of the port sector. The aim was to collect concrete examples. In particular, it was wanted to document real cases of implementation of the twelve good practices previously identified during the research.

This activity allowed for the integration of further empirical evidence and reinforced the validity and relevance of the selected practices through the analysis of concrete examples. Stakeholder engagement goes beyond mere data collection: it also informs the development of practical operational interventions and targeted training modules. The proposed sustainability practices are more likely to be accepted and implemented if those responsible for carrying them out are involved early in the evaluation and development process. When stakeholders actively contribute to formulating solutions, they are more motivated and empowered to adopt them. In this way, the acceptance of sustainability measures increases, as does the likelihood that these measures will be successfully implemented in the operational context.

Integrating a wide range of operational perspectives and adopting a rigorous methodological approach ensures that the selected practices are genuinely sustainable, efficient, and applicable. Furthermore, the active involvement of stakeholders enhances the practicality of the proposed solutions, improving the likelihood that they will be successfully adopted and implemented in port operations.

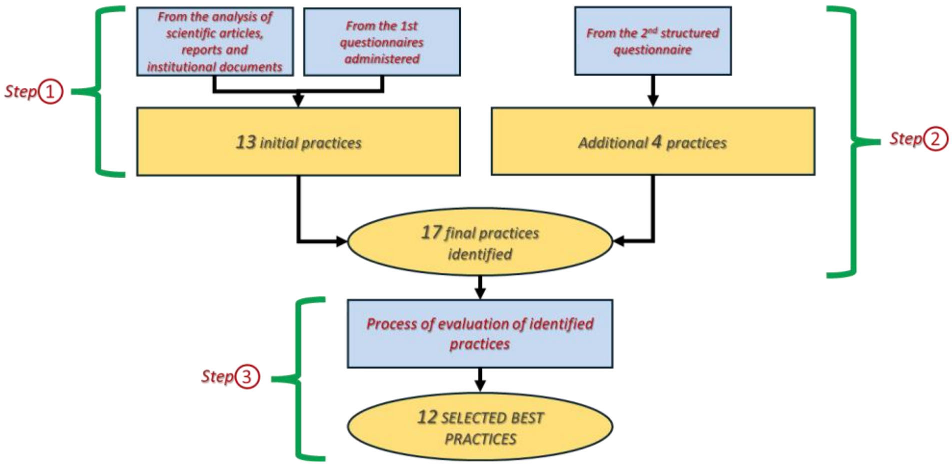
3.6 Data analysis methods

The qualitative data collected through desk research were analysed using thematic content analysis, a recognised method that allows researchers to identify, organise, interpret, and effectively report themes within textual data. This approach is particularly useful for exploring complex phenomena, such as sustainable practices in port operations [28,36]. Specifically, qualitative data from literature reviews, institutional documents, results from questionnaires, and the Case Study Identification Sheets administered were processed and coded using NVivo software. This tool is widely recognised as an effective resource for qualitative data analysis, helping to improve transparency, consistency, and replicability in the process of thematic coding and categorisation [37,43]. It supported the identification of major themes and practices, offering a clear and organised interpretation of the qualitative findings in line with the research aims and theoretical foundations. As a core component of this study, a dedicated "Case Study Identification Sheet" was developed to gather insights on the practical application of the sustainability practices identified previously. Stakeholders were encouraged to provide detailed descriptions of their specific operational contexts, outline any challenges they faced during implementation, document the results achieved, and explain how these sustainability measures corresponded with existing regulatory guidelines.

In addition, quantitative data were systematically collected through structured questionnaires directed at prominent stakeholders in port operations. The gathered responses were processed using Microsoft Excel, employing descriptive statistical techniques such as mean scores, standard deviations, and frequency distributions for each evaluated sustainability practice. By combining Likert-scale survey responses with these statistical methods, the analysis clearly captured stakeholder perspectives, effectively highlighting environmental, economic, social, technical, and institutional aspects [18,27,38]. The questionnaire featured both closed- and open-ended questions. Using this descriptive statistical approach was well-suited to evaluate perceptions of effectiveness, feasibility, and applicability of the practices among different stakeholder groups, enhancing the clarity of the findings and providing practical insights from the survey responses [39].

An integrated analytical methodology was employed, mixing insights derived from qualitative thematic analysis with quantitative assessments based on established evaluation criteria. By cross-validating results obtained from both qualitative and quantitative data sets, the robustness and dependability of the research findings were substantially improved [25,34,37]. This combined methodological framework ensured that the recommendations generated were strongly supported by empirical evidence and specifically customised to the unique operational contexts studied. The integration of qualitative depth and quantitative rigor enabled the formulation of actionable, stakeholder-validated strategies for reducing emissions and promoting sustainable operations in technical-nautical port services [18,38,39]. All collected data were anonymised and handled according to ethical research guidelines. Respondents gave their informed consent after being assured of the study's goal and the confidentiality of the data. The 1964 Helsinki Declaration, its subsequent revisions, and similar ethical guidelines were followed when conducting the study. In Figure 3 is explained the research design described above.

Figure 3 – Research design



4. Results and Discussion

4.1 Results

The evaluation process of sustainability practices in port operations was based on a set of specific parameters developed to assess the multidimensional effectiveness of each proposed solution. The evaluation revealed that five of the initially identified practices were not assessed by the respondents and were therefore excluded from the final phase of selecting the best practices. The remaining practices were evaluated through ten standardised parameters, with a scoring methodology that ensured consistency and objectivity by calculating the arithmetic mean of all stakeholder responses. The overall score of each sustainability practice was calculated as the average of the ratings provided by stakeholders on the different criteria. These aggregated scores made it possible to rank the practices. This made it possible to identify the most impactful and feasible solutions. Among the evaluated initiatives, "Continuous training and updates for pilots" received the highest score. This highlights the importance of continuous skills improvement to increase operational efficiency and achieve better environmental results. "Real-time route optimisation" and "Continuous emission monitoring" also received high scores. Both were praised for reducing fuel consumption and strengthening environmental management.

Practices targeting reductions in greenhouse gas emissions, like "Operational speed optimisation" and "Minimising engine running time", also stood out for their substantial potential to achieve fuel economy. While initiatives such as "Implementation of eco-friendly propulsion systems" necessitate considerable initial investments, their long-term benefits, such as lowered operational expenses and significant contributions to broader ecological transition goals, highlight their strategic significance for sustainable port management.

Stakeholder acceptance emerged as a key determinant influencing the practical feasibility of the recommended solutions. Initiatives such as continuous training and real-time emission monitoring received wide support. They were mainly appreciated for their immediate and tangible health and safety benefits. In contrast, more transformative practices, such as switching to alternative biofuels, met with more resistance. The main difficulties are related to technical obstacles in integration and the complexity of maintenance operations. Government support has played a key role in the success of these practices. Generally, support has been greatest for measures that are economically viable and comply with existing regulations. A coordinated effort between public institutions and private actors proved essential. This has accelerated the move towards a more sustainable navigation system.

Z-scores were applied to standardise the data to assist in comparing different practices—particularly regarding emission reductions, fuel efficiency, and other key metrics. Positive Z-scores indicated practices with a significantly positive impact compared to the other elements analysed, while negative scores highlighted areas for improvement.

Subsequently, the selected practices were validated in a few case studies, which were appropriately identified and provided concrete feedback on their applicability in real-world port settings. The case studies validated the effectiveness of the selected practices, showing that the solutions identified during the evaluation phase could be successfully applied in real operational settings. The implementation of the selected practices produced measurable improvements. In particular, benefits were observed in the reduction of emissions, optimisation of fuel consumption and overall operational sustainability. These results confirmed the empirical validity of the insights gained in the previous phases of the research. During the fieldwork phase, stakeholders provided new suggestions. Through open feedback, four new practices were proposed. Consequently, these additional practices were integrated into the initial list. At the same time, five of the original 13 practices were excluded. The decision was due to inadequate evaluation or lack of operational relevance. This iterative process culminated in a refined and validated final set of 12 practices, as illustrated in Figure 4.

Figure 4 - Ranking of the 12 best practices

				EVALUATION PARAMETERS										
# RANKING	CLUSTER (ID)	#	PRACTICE	Reduction of greenhouse gas emissions	Preservation of natural resources	Cost of implementation	Long-term operational savings	Acceptability among workers and the community	Improved health and safety	Ease of integration with legacy technologies	Maintainability and reliability	Compliance with environmental regulations	Support from government institutions	TOTAL SCORE
1	Cluster 3	12	Continuous training and updates for pilots.	4,50	3,00	5,00	5,00	4,00	5,00	3,00	4,00	5,00	3,00	4,15
2	Cluster 2	9	Real-time navigation route optimization.	3,50	4,00	5,00	5,00	4,00	3,00	4,00	5,00	4,00	3,00	4,05
3	Cluster 2	10	Continuous monitoring of emissions during operations.	4,25	5,00	4,00	4,00	2,00	5,00	3,00	4,00	5,00	3,00	3,93
4	Cluster 3	11	Behavioral change through training and awareness	4,17	4,33	4,00	4,00	3,67	4,00	3,67	3,67	4,00	3,67	3,92
5	Cluster 1	1	Implementation of eco-friendly propulsion systems.	4,29	4,29	4,29	4,29	3,71	4,29	2,71	3,86	3,86	3,29	3,89
6	Cluster 2	7	Optimization of operation speed.	4,83	4,00	4,33	4,33	4,33	3,00	4,67	4,67	2,00	2,67	3,88
7	Cluster 2	5	Collaboration among stakeholders for real-time data sharing	4,00	3,00	4,50	4,50	3,75	3,50	3,50	3,75	3,25	3,75	3,75
8	Cluster 1	4	Supply chain optimization	4,00	3,00	5,00	4,98	3,00	3,00	3,00	4,00	1,00	4,00	3,50
9	Cluster 2	8	Minimization of engine running time.	4,50	3,50	3,00	3,00	2,00	4,00	3,50	5,00	4,00	2,00	3,45
10	Cluster 1	2	Use of biofuels for tugboats.	3,83	3,50	3,17	3,17	2,83	3,33	2,50	3,00	3,67	3,00	3,20
11	Cluster 1	3	Regular maintenance of tugboat engines.	4,25	4,00	3,50	3,50	2,00	3,00	3,00	3,50	2,50	2,00	3,13
12	Cluster 2	6	Accurate route planning	3,50	2,25	3,25	3,25	3,50	2,25	3,00	3,50	2,75	2,25	2,95

The use of colour is intended to facilitate the visual interpretation of the ranking results. In particular, green highlights the highest values, which correspond to more favourable performances or evaluations. Red, on the other hand, indicates the lowest values, which reflect relatively less significant results. No fixed thresholds or absolute reference values were employed. Instead, the colour scale was determined exclusively by the relative ranking of scores. This method facilitates an intuitive comparative analysis of the data, avoiding the introduction of arbitrary evaluation benchmarks.

4.2. Discussion

The selected operational practices aim to generate substantial impacts across environmental, economic, and social dimensions. Each dimension was thoroughly evaluated, considering the distinctive attributes of port environments and the strategic objectives of the study, primarily promoting sustainability, enhancing operational efficiency, and improving local community welfare. The research outcomes support and expand existing theoretical perspectives, highlighting sustainability's multifaceted and interconnected nature in port operations [1,3,6,7].

From an environmental perspective, the identified practices specifically target a substantial reduction in the ecological impacts linked to port activities.

Particular emphasis is placed on curbing emissions of greenhouse gases and major air pollutants, including carbon dioxide (CO_2), nitrogen oxides (NO_x), sulphur oxides (SO_x), and fine particulate matter (PM10 and PM2.5), all of which contribute heavily to the deterioration of air quality in port areas. This reduction is pursued through the adoption of integrated strategies that include the optimisation of navigation routes, the introduction of eco-friendly propulsion systems (such as hybrid or electric engines), and the use of alternative fuels, such as biodiesel or liquefied natural gas (LNG). The emphasis on technological solutions—such as real-time emission monitoring, the electrification of port equipment, and the use of Onshore Power Supply (OPS) systems—reflects the growing consensus in the literature that innovation is a critical enabler of sustainable port logistics [1,3,6,7].

Among the implemented technologies, continuous emissions monitoring systems stand out as a critical advancement for achieving environmental sustainability. These systems enable real-time tracking of environmental performance for vehicles and port infrastructures, promptly identifying inefficiencies and facilitating rapid interventions to reduce ecological harm. Continuous monitoring not only improves operational effectiveness but also enhances transparency and accountability, providing measurable environmental progress to stakeholders and local communities.

Energy management is another key priority in sustainability efforts. By minimising energy waste through operational improvements and adopting energy-efficient technologies, ports can significantly decrease their environmental footprint and improve overall operational efficiency. One notable example is the use of OPS (Onshore Power Supply) systems, which allow ships to switch off their engines while docked, substantially cutting emissions and reducing noise pollution. Already operational in various European ports, OPS represents a tangible advancement toward the decarbonisation of maritime operations and supports achieving the climate goals set by the European Union.

The integrated approach to environmental sustainability aims to create a cultural and behavioural change within the port sector, raising awareness among operators about the importance of adopting ecologically responsible practices. This change is supported by continuous training programs and the integration of sustainability into educational pathways, with the goal of developing a new generation of professionals aware of their role in the ecological transition.

From an economic standpoint, the selected practices aim to enhance operational efficiency and reinforce the competitive position of ports by reducing costs linked to energy consumption, equipment maintenance, and resource management. Initiatives such as optimising navigation routes, minimising operational downtime, and adopting advanced technologies contribute directly to improving productivity, resulting in tangible cost savings and higher returns on investment. These outcomes align with existing research, which identifies operational optimisation—particularly within technical-nautical services like tugboat and pilotage operations—as a key driver of sustainability [15,17,18].

In addition, the shift toward sustainable practices creates new market opportunities, encouraging the growth of innovative sectors such as green energy production, electric mobility, and waste management. This integrated approach helps make ports more resilient and capable of facing future challenges in an increasingly competitive and sustainability-oriented global context.

The social dimension of the selected practices is evident in both stakeholder evaluations and the empirical case studies. Training programs and worker participation were consistently rated as impactful and feasible, emphasising the importance of human capital development alongside technological innovation. These findings corroborate earlier studies emphasising the limits of stand-alone technology adoption, and the need to embed behavioural and cultural change through education and engagement [19,20,24]. Stakeholder feedback highlighted that the successful implementation of new practices is more likely when personnel are involved from the early stages of planning and evaluation. This observation aligns with theoretical perspectives that stress the importance of social legitimacy and user engagement in driving the sustainable transformation of port services [24,28,30].

The analysis also highlighted the critical importance of institutional and community-level interactions in driving sustainability within port operations. Initiatives related to regulatory incentives, efforts toward greater transparency, and active stakeholder engagement were particularly well-received by respondents, aligning with prior research emphasising the significance of governance involving multiple actors and cohesive stakeholder collaboration [6,13,32]. This is particularly true for ports situated in environmentally vulnerable areas, where governance models that incorporate diverse stakeholder perspectives and balance regulatory adherence with community expectations can yield substantial benefits.

These findings collectively underscore the necessity of implementing a holistic, multidimensional evaluation framework that effectively integrates environmental, economic, social, technical, and institutional aspects. This integrated perspective reflects the complexity characteristic of contemporary port environments, emphasising strategic cooperation among port management, operational staff, technology firms, and institutional stakeholders. The results reaffirm that sustainable transformations in ports require not only advancements in technology but also dedicated human efforts, robust organisational support, and comprehensive governance frameworks [6,13,32].

4.3 Theoretical and managerial implications

This study presents an innovative theoretical framework for analysing port dynamics. It proposes managerial practices aimed at improving the sustainability and operational efficiency of the sector. The research is based on a multidimensional approach. It integrates environmental, economic, social, technical and institutional parameters into a single assessment model. This perspective allows for overcoming traditional sectoral analyses, which often focus on a single dimension of sustainability, and proposes a more comprehensive method for identifying and selecting the most effective operational practices [1,3,6,13].

The theoretical framework has been reinforced through rigorous desk research, which systematised key scientific and regulatory evidence on port sustainability, as well as through extensive field analysis to assess the applicability of the proposed model in real operational contexts. This study has brought to light the intricate interplay between technological innovation, human behaviour, and governance frameworks, emphasising that the successful adoption of new solutions requires the active participation of all actors within the port sector. It becomes evident that infrastructure projects or technological enhancements do not solely cover the path toward sustainable port development; they equally rely on integrating these advancements into a comprehensive strategy that aligns with port communities' economic and social priorities.

From a management point of view, the results offer useful indications for improving port operations. In particular, they highlight the importance of implementing strategies to reduce emissions and optimise resource consumption. It is also crucial to develop specialised training initiatives to strengthen organisational skills. The results show that the most effective pathways combine technological progress with organisational flexibility. This approach allows a gradual transformation of management practices. These insights are consistent with the most recent literature on the digitisation of ports. They emphasise the growing importance of data-driven decision-making, especially with regard to the adoption of digital tools and digital twinning systems [9,15,18].

In addition, training proves to be a key driver of transformation. It disseminates technical skills and industry-specific knowledge among different stakeholder groups. It also promotes large-scale operational improvements. To meet the diverse and evolving needs of the port sector, the study proposes a modular training architecture. A blended approach is recommended. This combines formal academic education, continuing vocational training for current workers and trainer training models. This approach is considered effective in accelerating the integration of sustainable practices throughout the port community.

In a rapidly evolving regulatory and technological landscape, the ability to continuously update and upskill personnel is a key factor in enhancing the overall competitiveness of the port system. These results further support the literature that emphasises the importance of behavioural training and engagement in the successful implementation of sustainability strategies [23,24,28].

The results of the qualitative and quantitative analyses confirm the importance of collaboration between the various actors in port operations. The active participation of ports, institutional bodies, trade associations and local stakeholders is crucial. It serves to promote transparent governance structures and to achieve long-term strategic objectives. Strengthening cooperation between institutions facilitates the implementation of coordinated sustainability strategies. It also helps to overcome difficulties caused by fragmented responsibilities and different regulatory frameworks in port ecosystems. Besides contributing to the academic debate on the sustainable management of port services, the methodological framework proposed in this study offers a practical tool. It is useful for guiding strategic decisions in the sector. The analysis of collected data and evidence enables the identification of actionable solutions and the formulation of strategic recommendations beneficial to industry operators. This reinforces prior findings about the role of institutional incentives and participatory stakeholder approaches in enabling effective transitions [6,13,28]. The results of the study underscore the importance of adopting an integrated vision of sustainability—one that goes beyond mere regulatory compliance to also strengthen operational efficiency and enhance the global competitiveness of European ports. Achieving a more sustainable and efficient port system requires a fundamental reorientation of management strategies, where the adoption of technological innovations is accompanied by deep cultural and organisational change. Sustainable growth in the sector can only be realised through a systemic and collaborative approach that addresses the interconnected challenges posed by both ecological imperatives and the ongoing digital transformation.

5. Conclusion

Through the analysis, 12 operational practices were identified as particularly effective in advancing port operations' environmental and economic sustainability. These practices can be summarised in three main pillars: reducing emissions, improving operational efficiency, and strengthening stakeholder engagement through training and awareness initiatives.

The first pillar focuses on mitigating the environmental impact of port activities by promoting low-emission technologies, optimising fuel consumption, and implementing systems for continuous environmental monitoring. The second pillar addresses the enhancement of resource and process management, emphasising strategies such as route optimisation and deploying advanced digital tools for real-time energy monitoring. The third pillar highlights the importance of human capital, advocating for continuous training programs that foster proactive and sustainable resource management behaviours among port personnel.

Case study evidence clearly indicates that the implementation of these practices has begun to produce measurable benefits. Ports that have integrated these sustainability measures report meaningful reductions in emissions, decreased energy consumption, and notable improvements in safety conditions for port workers. From an environmental standpoint, the measures effectively reduce greenhouse gas emissions, optimise energy efficiency, and mitigate detrimental impacts on coastal and marine ecosystems.

On the economic side, the adoption of these practices leads to substantial operational cost reductions through improved resource efficiency and provides better access to incentives related to green financing. Socially, these measures significantly enhance workplace conditions and foster increased environmental consciousness among port employees.

In addition to immediate outcomes, this research presents a clear, structured, and data-informed guide for port authorities and maritime operators, facilitating more effective prioritisation and implementation of sustainability actions. Nevertheless, to achieve enduring results, two pivotal aspects must be addressed: strengthening institutional collaboration to guarantee widespread acceptance, and promoting a shift in organisational culture that prioritises responsible environmental management practices among all involved stakeholders. Lastly, the research underscores the importance of conducting longitudinal studies to evaluate the sustained effectiveness of these practices over time, while also recommending the extension of the developed evaluation framework to additional logistics and transportation contexts to enhance its generalizability and overall impact.

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