ISSN 0554-6397
UDK: 004.032.26
Review Article
Received: 10th January 2026.

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The Analysis on Sustainable Maritime Supply Chains and Port Operations in Main European Ports

Abstract

This paper highlights the importance of smart port technologies in optimizing operations and reducing gas emissions in major European ports. It analyzes the implementation of technologies such as automation, AI, IoT, Digital Twin, and Big Data in five major ports – Rotterdam, Antwerp-Bruges, Hamburg, Valencia, and Piraeus – and their contributions to reducing CO_2 emissions and improving efficiency. Through comparative analysis, the paper examines how these innovations support faster vessel turnaround, supply chain transparency, predictive maintenance, and real-time emissions tracking. The methodology is based on the analysis of secondary data. The paper uses synthesis to integrate diverse data, description to explain specific technology applications, and comparison to assess similarities and differences between ports. Findings indicate that smart technologies positively impact throughput, cost efficiency, and emission reduction. However, the extent of the impact varies due to factors such as port size, local context, and technological maturity.

Keywords: smart port technologies, maritime supply chain, European ports, port operational efficiency, sustainability

1. Introduction

New technological solutions, such as the Internet of Things and Big Data technology, are creating significant potential for industrial development and advancing supply chain management and logistics. The transition to smart shipping marks a major step in the evolution of international shipping, involving the integration of ships and ports with modern technology. The goal is to make international shipping and supply chains more accountable, efficient, environmentally friendly, and competitive by improving decision-making, reducing costs, and minimizing environmental impact.

This paper analyzes how five major European ports implement smart technologies to enhance operational efficiency and reduce CO_2 emissions. It examines the relationship between digital and green innovations and the sustainability performance of port operations. Through comparative analysis, the paper evaluates how technologies such as automation and digitalization contribute to emission reduction, productivity improvement, and cost efficiency. The main objective is to identify which smart technologies are currently in use, assess their impact on environmental performance, and evaluate their role in improving operational efficiency and competitiveness.

The paper comprises six main sections, providing a comprehensive analysis of the role of smart technologies in enhancing efficiency and sustainability in European ports. The introduction defines the aim of the research and presents the main research question and structure of the paper. The literature review summarizes previous studies on supply chains, Industry 4.0, and the development of smart ports. The methodology section describes the data and methods used for the analysis. The results section presents the main findings. In the discussion, the results are interpreted and compared. Finally, the conclusion summarizes the main findings, acknowledges the limitations, and suggests directions for future research on digital and sustainable transformation in ports.

2. Literature review

A review of the literature on logistics and supply chains shows that there is no universally accepted definition of the supply chain, as interpretations vary depending on authors' perspectives and contexts. Generally, it is described as a coordinated network of companies collaborating to deliver products or services to the end customer [10]. The concept includes the flow of goods, services, and information from suppliers to consumers through manufacturers, distributors, and retailers [6]. A traditional supply chain consists of procurement, manufacturing, and distribution phases, which may operate across multiple regions. The main goal of supply chain management is to ensure efficient and coordinated movement of materials, information, and finances from suppliers to end customers [17]. Maritime supply chains (MSC) include seaports and shipping operations that facilitate over 80% of global trade [29]. They involve a wide range of stakeholders, such as shipping companies, freight forwarders, port authorities, and inland carriers, all collaborating to ensure a smooth transport of goods across international waters [28, 9]. The MSC operates as an integrated network coordinating maritime transport from origin to final destination, serving as a critical connector within global supply networks [12].

Traditionally, maritime supply chains rely on both paper-based and electronic documentation and are often hindered by fragmented information sharing among stakeholders. Ports play a central role in these systems, acting as strategic logistics hubs that connect supply and demand and manage trade flows efficiently [11]. Modern ports have evolved beyond cargo handling to become integrated logistics platforms supporting sustainability, innovation, and resilience in supply chains [7].

2.1. Sustainability in maritime supply chains with the emphasis on ports

Sustainability has become a global priority across industries, integrating environmental, social, and economic dimensions. It is defined as meeting present needs without compromising the ability of future generations to meet their own. Environmental sustainability focuses on efficient resource use, pollution reduction, and biodiversity protection, supported by principles such as the 4Rs (Refuse, Reuse, Reduce, Recycle).

The European Union recognizes sustainable development as a key objective, aligning its policies with the United Nations 2030 Sustainable Development Goals (SDGs). Shipping, while essential for global trade, presents major environmental challenges, including greenhouse gas emissions, pollution, and habitat damage [17]. The International Maritime Organization (IMO) has introduced global measures such as MARPOL and fuel sulfur limits to mitigate these effects. In the maritime sector, sustainable port management emphasizes balancing safety, environmental responsibility, and economic efficiency. The World Ports Sustainability Program [30] highlights port contributions to the SDGs, particularly focusing on innovation (SDG 9), sustainable cities (SDG 11), and economic growth (SDG 8), though social issues such as poverty and gender equality remain less prioritized.

2.2. Smart port technologies

Positioned within a complex network of industrial and transport systems, ports face increasing demands to expand infrastructure and adopt sustainable, technologically advanced practices [13]. The rise of Industry 4.0 has accelerated the transformation of ports into “smart ports,” integrating digital solutions to enhance efficiency, reduce costs, and minimize environmental impact [15].

Smart port technologies include the Internet of Things (IoT), automation, Artificial Intelligence (AI), Big Data Analytics, Digital Twins, and Blockchain. While these are not the only smart port technologies, they are the most prominent. IoT enables interconnected devices to exchange data in real time, improving asset monitoring and operational control [16]. Automation reduces human error and increases productivity through automated container handling and terminal operations, achieving cost reductions of up to 50% [11]. AI improves decision-making by predicting vessel arrivals and optimizing port traffic, resulting in reduced congestion and emissions.

Big data technologies process large volumes of information, enabling predictive analysis and performance simulations such as digital twin models, which create real-time virtual replicas of port operations to support planning and emissions monitoring [8]. Blockchain ensures secure, transparent, and efficient transactions, reducing administrative costs and improving traceability across logistics networks [1].

Collectively, these technologies enable ports to operate more sustainably, increasing throughput and resilience while supporting the global transition toward low-carbon logistics. Smart ports represent a strategic response to the dual challenge of maintaining competitiveness and achieving environmental objectives within the evolving framework of maritime Industry 4.0. Technologies such as digital twins support predictive maintenance, resource optimization, and environmentally responsible operations, aligning with global sustainability goals like the UN 2030 Agenda [5]. Smart ports attract more cargo traffic by offering improved service quality, lower costs, and greater capacity [2].

3. Research methodology and conceptualization of operational efficiency in ports

Operational efficiency in ports refers to a port's ability to utilize its available resources, such as infrastructure, equipment, labor, and technology, to maximize port performance while maintaining cost-effective operations. In literature on port economics, operational efficiency is typically assessed using a combination of operational indicators (cargo throughput, vessel turnaround time, crane productivity etc.) and financial indicators that reflect the economic outcomes of port activities. Cargo throughput is one of the most widely used operational indicators, representing the total volume of cargo handled within a port over a specific period. Throughput is often used as a proxy for operational performance because it reflects the port's capacity utilization and its role within logistics networks. Higher throughput levels generally indicate more intensive use of port infrastructure and improved operational performance [3, 4, 11].

In addition to operational indicators, financial performance indicators are used to evaluate the economic dimension of port efficiency. Financial metrics provide insight into how effectively port operators convert operational activity into economic value and business performance. Due to the lack of financial data that directly measure the operational efficiency of European ports, financial performance is assessed using total operating income, total operating expenses, EBITDA, and net income. These indicators capture different aspects of financial efficiency, revenue generation from port operations, cost management, operational profitability, and overall financial outcomes.

Interpretation is supplemented with qualitative information on implemented technologies and specific operational outcomes (emission reduction, handling time, and number of operations per hour) to ensure a reliable assessment of how smart technologies impact operational efficiency.

The combined use of operational and financial indicators allows for a broader assessment of port performance. While throughput reflects the physical dimension of port activity, financial indicators show whether increased operational activity translates into improved economic performance. This integrated approach is particularly relevant when analyzing the impact of technological development in ports, as modern port technologies aim not only to increase cargo handling capacity but also to improve operational efficiency.

The analysis is based on secondary data from existing sources, including scientific papers, case studies, articles, and reports from governmental and business associations. It covers major European ports that serve as key entry points, connecting their transportation networks to the global community. Table 1 presents the largest European ports by container traffic for 2024, ranked by TEU (twenty-foot equivalent units).

Table 1. Largest European ports according to container traffic.

Port	Country	TEU 2024	Range
Rotterdam	Netherlands	13.820.000	1
Antwerp-Bruges	Belgium	13.500.000	2
Hamburg	Germany	7.800.000	3
Valencia	Spain	5.475.773	4
Pireus	Greece	4.826.000	5

Source: Authors based on PortEconomics 2024.

The most important European ports critical to the economy are Rotterdam, Antwerp-Bruges, and Hamburg, which dominate container traffic, as well as Valencia and Piraeus, which serve as vital regional hubs.

4. Results

In the EU, 4 million people travel by sea each year, and the maritime industry accounts for 35% of internal and 77% of external trade (a total of 4 billion tons). In addition to being excellent for transporting goods, ports also serve as energy centers for both conventional and renewable energy sources.

4.1. Port of Rotterdam

Table 2 presents Scope 1 CO_2 emissions from 2019 to 2024 for the Port of Rotterdam, including actual figures and progress toward long-term, scientifically established climate targets for 2030.

Table 2. Port of Rotterdam CO_2 emissions in Scope 1, 2019 – 2024.

In gross ton CO_2eq	2024	2023	2022	2021	2020	2019	Realization 2019 – 2023	Science based target 2019 – 2030
Scope 1								
Own vessels and vehicles, and own real estate	692	1582	2600	2645	2992	3242	-79%	-90%

Source: [19]

From 2019 to 2024, CO_2 emissions from own vessels, vehicles, and real estate decreased significantly, from 3,242 tons in 2019 to 692 tons in 2024. This represents a 79% reduction in Scope 1 CO_2 emissions. This progress indicates a successful implementation of sustainable measures, such as adopting electric vehicles and smart cranes. Table 3 presents the throughput of the Port of Rotterdam for the period 2020 – 2024.

Table 3. Throughput in the Port of Rotterdam 2020 – 2024.

Year	Throughput (in million tons)	% change throughput
2020	436.8	
2021	468.7	7.3
2022	467.4	-0.3
2023	438.8	-6.1
2024	435.8	-0.7

Source: Authors based on [20]

The Port of Rotterdam handled 436.8 million tons of cargo in 2020, reflecting the severe impact of the COVID-19 pandemic on global supply chains. Throughput rebounded in 2021 to 468.7 million tons (a 7.3% increase), reaching pre-pandemic levels, mainly driven by container traffic (Rotterdam Port Authority, 2022). In 2022, throughput declined slightly by 0.3% to 467.4 million tons, indicating market stabilization, followed by a sharper 6.1% drop in 2023 to 438.8 million tons due to reduced industrial activity, geopolitical tensions, and energy disruptions. In 2024, throughput decreased marginally by 0.7% to 435.8 million tons, mainly because of declining coal and crude oil volumes amid European energy transition [17]. Table 4 presents the financial report of the Port of Rotterdam for the period 2020 – 2024.

Table 4. Port of Rotterdam Annual Financial Report 2020 – 2024.

Year	Total operating income	Total operating expenses	EBITDA	Net income
2020	753.255	437.151	316.104	351.718
2021	772.723	450.436	273.614	247.267
2022	825.664	459.936	318.369	247.243
2023	841.509	480.154	361.355	309.059
2024	882.001	497.468	384.533	273.727

Source: Authors based on [19]

Between 2020 and 2024, the operating income of the Port of Rotterdam increased from 753.3 million euros to 882.0 million euros (+17.1%), while expenses rose by 13.8%, indicating improved efficiency. The decline in CO_2 emissions in the Port of Rotterdam from 2019 to 2024 coincided with the increase in operating income between 2020 and 2024. EBITDA declined by 13.5% in 2021 but recovered in 2022, surpassing 2020 levels. Net income fluctuated, rising by 24.9% in 2023 before falling by 11.4% in 2024 due to higher taxes and depreciation. Overall, the port maintained strong revenue growth and operational resilience despite external pressures.

From 2020 to 2024, the Port of Rotterdam experienced fluctuating throughput trends influenced by global shocks and structural changes. Cargo volumes rebounded after the pandemic, reaching 468.7 million tons in 2021, but declined again in 2023 – 2024 due to reduced fossil fuel imports and the European energy transition [19].

4.2. Port of Antwerp-Bruges

The Port of Antwerp-Bruges uses digital twin, AI, and autonomous drone technologies to improve efficiency and environmental monitoring. The APICA platform integrates real-time data, automates decision-making, and enhances situational awareness. Through the Antwerp@C project, major industry partners are developing carbon capture and storage systems to reduce CO_2 emissions by up to 50% by 2030 and achieve climate neutrality by 2050 [21]. Table 5 presents the total throughput of the Port of Antwerp for 2020 – 2024.

Table 5. Port of Antwerp Total Throughput 2020-2024

Year	Throughput (in million tons)	% change throughput
2020	231	
2021	240	+3.8%
2022	286.9	+19.5%
2023	271	-5.5%
2024	278	+2.3%

Source: Authors based on [21]

Between 2020 and 2024, the Port of Antwerp-Bruges demonstrated a generally positive throughput trend, with brief fluctuations reflecting global and local dynamics. The introduction of digital twin, AI, and autonomous drone technologies at the Port of Antwerp coincided with an increase in cargo throughput during this period. Despite the pandemic, total cargo reached 231 million tons in 2020 and increased to 240 million tons in 2021, marking an initial recovery.

The 2022 merger of Antwerp and Zeebrugge led to a sharp 19.5% increase, reaching 286.9 million tons. Throughput then declined by 5.5% in 2023 but rebounded slightly in 2024 to 278 million tons (+2.6%), indicating market stabilization and the port's adaptability. Comprehensive financial data for 2020 – 2024 are unavailable, as official reports mainly include operational indicators rather than profit and loss statements. This limits deeper financial evaluation, yet operational figures demonstrate resilience and long-term growth potential.

4.3. Port of Hamburg

The Port of Hamburg's smartPORT initiative integrates logistics and energy systems to reduce emissions and enhance sustainability. SmartPORT Energy supports renewable energy, efficiency, and low-emission transport, while IoT and digital twins have reduced downtime by 30% [22]. At Hamburg Port and Logistics Corporation (HHLA) Altenwerder terminal, battery-powered vehicles save 5 million liters of diesel and reduce CO_2 emissions by 15,500 tons annually [23]. Smart lighting reduces energy consumption by 80%, contributing to a 42% reduction in CO_2 emissions since 2018, with targets of a 50% reduction by 2030 and climate neutrality by 2040 [24]. Table 6 shows the total throughput of the Port of Hamburg from 2020 to 2024.

Table 6. Port of Hamburg total throughput 2020 – 2024.

Year	Throughput (in million tonnes)	% change throughput
2020	126.3	
2021	128.7	+1.90%
2022	119.9	-6.83%
2023	114.3	-4.67%
2024	111.8	-2.19%

Source: Authors based on [18]

The Port of Hamburg's throughput declined steadily from 2020 to 2024. After a slight post-pandemic recovery from 126.3 million tons in 2020 to 128.7 million tons in 2021, volumes began to decrease. Throughput is estimated at 119.9 million tons in 2022, reflecting the impact of global trade slowdowns and geopolitical instability. The decline continued to 114.3 million tons in 2023 (–4.7%) and 111.8 million tons in 2024 (–2.2%). This sustained downturn highlights structural challenges such as shifting supply chain patterns, competition among European ports, and the broader effects of the energy transition. Table 7 presents the financial report of the Port of Hamburg for 2020 – 2024.

Table 7. Port of Hamburg financial report 2020 – 2024.

Year	Total operating income	Total operating expenses	EBITDA	Net income
2020	1.36 billion	1.07 billion	289.4 million	74.1 million
2021	1.52 billion	1.12 billion	406.7 million	132.9 million
2022	1.63 billion	1.24 billion	396.3 million	133.1 million
2023	1.53 billion	1.24 billion	287.8 million	42.4 million
2024	1.68 billion	1.37 billion	309 million	56.4 million

Source: Authors based on [24]

Between 2020 and 2024, Hamburg Port and Logistics Corporation (HHLA) reported both growth and volatility in its financial results. Operating income rose steadily from 1.3 billion euros in 2020 to 1.68 billion euros in 2024, while expenses increased from 1.12 billion euros to 1.37 billion euros. Net income fluctuated significantly, rising from 74 million euros in 2020 to 133 million euros in 2021 – 2022, then dropping to 42 million euros in 2023 before recovering slightly to 56 million euros in 2024. The decline in 2023 was mainly due to higher financial expenditures, particularly a notable increase in interest charges, which reduced profitability. As with the Port of Rotterdam, the smartPORT initiative in the Port of Hamburg coincides with the observed increase in financial performance between 2020 and 2024.

4.4. Port of Valencia

The Port of Valencia promotes innovation through FV17, a research and skills development hub established by the Port Authority in collaboration with local partners. It was one of the first ports in Europe to launch a private 5G Stand-Alone network, connecting over 25,000 devices – including drones, vehicles, and sensors – to improve cargo control, security, and efficiency. The €6 million project, co-funded by the EU, also supports digital twin simulations for real-time port management. As part of the "Valenciaport 2030, Zero Emissions" plan, the port uses IoT sensors to monitor air and noise quality within the Green C Ports project. Despite a 24% increase in traffic, the port maintained a stable carbon footprint and achieved a 17% reduction in CO_2 emissions since 2008. Table 8 presents the total throughput at the Port of Valencia for the period 2020 – 2024.

Table 8. Port of Valencia total throughput 2020 – 2024.

Year	Throughput (in million tons)	% change throughput
2020	80.8	
2021	85.4	+5.42%
2022	79.4	-7.03%
2023	77.1	-2.90%
2024	81.1	+5.19%

Source: Authors based on [25]

Cargo throughput at the Port of Valencia fluctuated between 2020 and 2024, reflecting broader global trade trends. After handling 80.8 million tons in 2020, volumes rose by 5.4% in 2021 to 85.4 million tons, marking a strong post-pandemic recovery. However, throughput then dropped to 79.4 million tons in 2022 (–7%) and 77.1 million tons in 2023 (–2.9%) amid inflation and supply chain disruptions. The observed increase in cargo throughput corresponds with the implementation of smart port technologies in Port of Valencia in the observed period. In 2024, activity rebounded by 5.2%, reaching 81.1 million tons. Table 9 presents the financial report of the Port of Valencia for 2018 – 2022.

Table 9. Port of Valencia financial report 2018 – 2022.

Year	Total operating income	Total operating expenses	EBITDA	Net income
2018	138.1 mil.	137.6 mil.	76.4 mil.	33.3 mil.
2019	138.9 mil.	137.7 mil.	76.9 mil.	19.3 mil.
2020	133.6 mil.	110.5 mil.	72.4 mil.	26.5 mil.
2021	143.1 mil.	117.5 mil.	73.2 mil.	30.9 mil.
2022	144.9 mil.	119.6 mil.	82.8 mil.	31.4 mil.

Source: Authors based on [25]

The Port Authority of Valencia showed strong financial resilience from 2018 to 2022. Operating income remained stable, ranging from 138.1 million euros in 2018 to 144.9 million euros in 2022, with a temporary decline in 2020 due to the pandemic. Operating expenses followed a similar pattern, decreasing in 2020 but rising again to 119.6 million euros in 2022. EBITDA consistently ranged between 72 and 76 million euros, peaking at 82.8 million euros in 2022, reflecting strong operational efficiency. Net income fluctuated but increased steadily, reaching 31.4 million euros in 2022, its highest level since 2018. The financial indicators also positively correspond with the implementation of smart port technologies in Port of Valencia in the observed period.

4.5. Port of Piraeus

In 2021, the Piraeus Port Authority (PPA) and Vodafone launched a private LTE network at the Piraeus Container Terminal, enabling real-time monitoring through NB-IoT technology. This system allows continuous data transfer between terminals, improving efficiency, safety, and resource management while reducing paper waste. As an EcoPorts member, Piraeus complies with EU and IMO environmental standards and participates in projects such as Poseidomed II and Green and Connected Ports. According to the Piraeus Container Terminal (PCT) Sustainability Report [24], total CO_2 emissions decreased by 21% in 2023 compared to 2022, and electricity use dropped by 3%, demonstrating measurable sustainability progress.

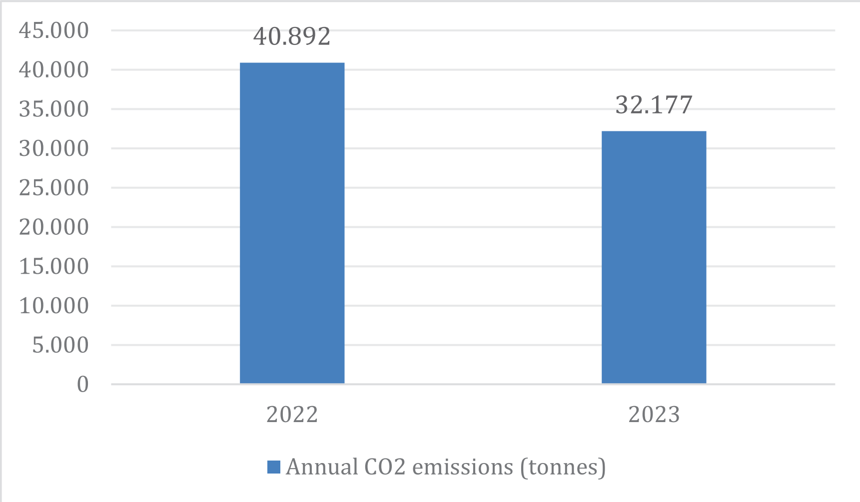

Figure 1. Annual CO_2 emissions (tons of CO_2 equivalent).
Source: Authors based on [26]

Figure 1 shows a significant decrease in CO_2-equivalent emissions at the Port of Piraeus between 2022 and 2023. Emissions dropped from 40,892 tons CO_2eq in 2022 to 32,177 tons CO_2eq in 2023, representing a 21% reduction. Two contrasting bars clearly illustrate this downward trend, highlighting the port's progress in reducing environmental impact through digitalization and energy efficiency measures. Table 10 presents the financial report of the Port of Piraeus for the period 2019 – 2023.

Table 10. Port of Piraeus financial report 2019 – 2023.

Year	Total operating income	Total operating expenses	EBITDA	Net income
2019	50.2 mil.	29.2 mil.	/	35.4 mil.
2020	40.9 mil.	25.3 mil.	/	26.4 mil.
2021	52.4 mil.	29.2 mil.	/	36.8 mil.
2022	77.2 mil.	39.3 mil.	/	52.9 mil.
2023	97.3 mil.	34.4 mil.	/	66.8 mil.

Source: Authors based on [27]

Despite this, the Port of Piraeus Financial Report (2019 – 2023) shows a clear upward trend in both revenue and net income. Operating income nearly doubled from

50.2 million euros in 2019 to 97.3 million euros in 2023, driven by strong growth in 2022 (47.3%) and 2023 (26%). Operating expenses remained stable at around 29 million euros until 2021, then rose to 39.3 million euros in 2022, likely due to inflation or expansion, before falling to 34.4 million euros in 2023, indicating improved efficiency and cost control.

Net income increased from 35.4 million euros in 2019 to 66.8 million euros in 2023, with a temporary drop to 26.4 million euros in 2020 caused by the COVID-19 pandemic. The subsequent recovery demonstrates strong financial resilience. While many ports implementing smart technologies report improved throughput and cost efficiency, these gains may also reflect capital investments or broader economic factors. However, evidence from the Port of Rotterdam suggests a link between digital tools such as PMS and OR systems and measurable performance improvements.

Table 11 presents a synthetic comparative table of key technologies implemented in ports, along with the average annual percentage change and Compound Annual Growth Rate (CAGR) for cargo throughput and net income in all five ports from 2020 to 2024. The average annual change indicates volatility or fluctuations, while the CAGR reflects the overall or underlying trend.

The authors performed the calculations using data from Tables 3 to 10. The average annual percentage change is calculated as the year-to-year percentage change, followed by computing the arithmetic mean. The CAGR is calculated using the following formula:

$$\text{CAGR}=\left(\frac{Final\ value}{Initial\ Value}\right)^{\frac{1}{n}}-1 \qquad [1]$$

Table 11. Synthetic comparative table for all five ports in 2020 – 2024.

Port	**Key technologies implemented**	**Cargo throughput average annual % change**	**Cargo throughput CAGR**	**Net income average annual % change**	**Net income CAGR**
Rotterdam	Sustainable measures	+0.06%	-0.06%	-4.03%	-6.06%
Antwerp-Bruges	digital twin, AI, autonomous drones	+5.12%	+4.74%	No data	No data
Hamburg	SmartPORT energy, IoT, digital twin	-2.95%	-3.01%	+11.10%	-6.64%

Valencia	5G Stand-Alone network, IoT, drones	+0.24%	+0.09%	+9.11% (years 2020-2022)	+8.86% (years 2020-2022)
Pireus	LTE network, NB-IoT technology	No data	No data	+36.97% (2020-2023)	+33.7% (2020-2023)

Source: Authors' calculations

Despite a few brief fluctuations, the port of Rotterdam cargo throughput remained relatively steady over the observed period, with an average annual change of about 0.06%. Although there were short-term variations, the CAGR of cargo throughput between 2020 and 2024 indicates a slight average annual decrease of approximately 0.06%, reflecting overall stability in cargo volumes. In contrast, while the CAGR shows a general downward trend of about -6.06% for net income between 2020 and 2024, net income displays significant volatility during the examined period, with an average annual change of -4.03%.

With an average annual growth rate of 5.12%, cargo throughput at the port of Antwerp-Bruges shows a positive trend over the studied period. Despite brief fluctuations, the 4.74% CAGR indicates consistent medium-term growth.

Cargo throughput at the port of Hamburg is declining, with an average annual decrease of 2.95% and a CAGR of -3.01% between 2020 and 2024. Financial performance, as measured by net income, is highly volatile, with an average annual change of +11.10%. However, the CAGR of -6.64% indicates an overall downward financial trend during the studied period.

The Port of Valencia cargo throughput remained steady from 2020 to 2024. The average annual growth rate of 0.24% and a CAGR of 0.09% indicate a stable long-term trend, despite some year-to-year fluctuations. With an average annual net income growth of 9.11% and a CAGR of 8.86% between 2020 and 2022, the Port of Valencia demonstrated strong financial performance during the observation period.

Between 2020 and 2023, the Port of Piraeus net income increased significantly. The CAGR of 33.7% indicates a consistent upward trend in financial performance, although year-to-year variations are notable, with an average annual growth of approximately 36.97%. This pattern suggests a steady increase in profitability, likely resulting from both operational improvements and effective management practices.

5. Discussion

This paper evaluated the impact of implementing smart technology to improve operating efficiency and reduce greenhouse gas emissions in five major European ports: Rotterdam, Antwerp-Bruges, Hamburg, Valencia, and Piraeus. The analysis drew on published emissions reports, financial results, established technological solutions, and available secondary traffic data. The results show that smart technology provides benefits, particularly in Rotterdam and Hamburg, where there are clear operational and environmental advantages, including lower CO_2 emissions, increased handling capacity, and reduced operating costs. Although on a smaller scale, ports such as Piraeus have also achieved notable operating savings and pollution reductions. However, despite significant digitization, Antwerp-Bruges and Valencia have not yet provided sufficient quantitative data to establish a direct link between smart technology and measurable improvements in operational efficiency and emission reductions.

The findings do not confirm a direct causal relationship between the implementation of smart technological solutions in ports and changes in cargo throughput or financial performance. However, in most cases, during the period when these technologies were implemented, the physical and financial performance of ports remained stable or showed an upward trend, with occasional fluctuations. It should also be noted that an adjustment period is often required, as the full effects of technological investments in ports are more likely to become visible over the longer term.

6. Conclusion

This paper examined how five major European ports implement smart technologies to enhance operational efficiency and reduce emissions, focusing on the impact of digital and green innovations on sustainability performance. In this research, operational efficiency is conceptualized as the combined performance outcome of cargo handling activity and financial results, measured through throughput (in million tons) and selected financial indicators, enabling a longitudinal comparison of performance trends across the analyzed European ports.

The paper identified the smart and sustainable technologies currently in use, confirming that these innovations help reduce environmental impacts. Additionally, the paper evaluated how these technologies influence port productivity and competitiveness, finding improvements in throughput, cost reduction, and energy efficiency.

The findings partially support the research hypothesis that integrating smart technologies into port systems increases operational efficiency and reduces gas emissions. Although there is qualitative evidence linking smart technologies to improved port outcomes, methodological limitations prevent full confirmation of this relationship. The findings do not confirm a direct causal relationship between the implementation of smart technological solutions in ports and changes in cargo throughput or financial performance. However, in most cases, during the period when these technologies were implemented, the physical and financial performance of ports remained stable or showed an upward trend, with occasional fluctuations. It should also be noted that an adjustment period is often required, as the full effects of technological investments in ports are more likely to become visible over the longer term. Nonetheless, this research highlights key success factors and barriers in deploying smart port technologies and underscores their essential role in advancing sustainable maritime logistics aligned with EU green and digital transformation goals.

This paper has some limitations. First, no primary data were collected; only secondary data were used. Second, no quantitative econometric techniques were applied to assess the direction or extent of causal relationships. Third, it was not possible to isolate or control the effects of other contextual variables. Despite these limitations, the paper provides valuable insights into how smart port technologies contribute to effective and sustainable maritime logistics. The results demonstrate the crucial role of digital transformation in maintaining port competitiveness, reducing environmental impacts, and promoting international trade.

Funding

This research was funded within the scope of the project "Supply chain transparency and resilience – the perspective of small and medium-sized enterprises" (uniri-mz-25-7), funded by European Union – NextGenerationEU via the Croatian National Recovery and Resilience Plan 2021-2026, in conjunction with the University of Rijeka, Faculty of Economics and Business Programme Financing.

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