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Assessment of Port Digitalization: Revealing the Current Research Trends and Technologies

Liman Dijitalleşmesinin Değerlendirilmesi: Mevcut Araştırma Eğilimleri ve Teknolojilerinin Ortaya Çıkarılması

Türk Denizcilik ve Deniz Bilimleri Dergisi

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ABSTRACT

This study aims to examine digitalization processes in port operations, identify current research trends and technologies, and provide recommendations for future studies aligned with these developments. To achieve these objectives, a comprehensive literature review was conducted. Initially, a detailed analysis of existing studies was performed, including the creation of keyword and country heat maps. Subsequently, the literature was examined using VOSviewer software. Bibliographic coupling analysis showed that the studies fell into four main clusters. The findings indicate that port digitalization is playing a significant role in transforming the sector. Despite a substantial body of research, several areas remain underexplored and open to further development. Key topics identified for future investigation include cost-benefit analyses of digitalization and the adaptation of operational processes to digital technologies.

Keywords: Maritime transportation, Ports, Digitalization, Sustainability, VOSviewer

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ÖZET

Bu çalışmanın amacı liman işletmelerindeki dijitalizasyon süreçlerini incelemek, mevcut çalışma trendlerini ve teknolojilerini ortaya koymak ve bu trendler doğrultusunda gelecek çalışmalara öneriler sunmaktır. Bu amacı gerçekleştirmek için kapsamlı literatür taraması gerçekleştirilmiştir. İlk olarak çalışmaların anahtar kelime ve ülke yoğunluk haritası analizi yapılmıştır. Sonrasında literatür taraması yöntem olarak VOSviewer programıyla analiz edilmiş ve bibliographic coupling yöntemiyle çalışmalar 4 temel kümeye ayrılmıştır. Elde edilen sonuçlar doğrultusunda liman dijitalizasyonunun sektöründe şekillenmesinde önemli bir güç olduğu görülmüştür. İlgili literatür göz önünde bulundurulduğunda bu alanda birçok çalışmanın gerçekleştirildiği ancak hala açık ve geliştirilebilir alanların da olduğu gözlemlenmiştir. Geliştirmeye açık alanlardan bazıları, dijitalizasyonun fayda maliyet analizleri, dijitalizasyon ve diijtal teknolojilere adaptasyon süreçleri gibi konuların olduğu ortaya çıkmıştır.

Anahtar sözcükler: Deniz taşımacılığı, limanlar, dijitalizasyon, sürdürülebilirlik, VOSviewer

1. INTRODUCTION

Digitalization is playing an important role in maritime transportation, with its effects changing almost all business features and styles (Dehning *et al.,* 2003). Most sectors have begun investing in digitalization in relevant departments. This transformation covers changing the organizational, business capabilities in organizations (Tijan *et al.,* 2021a). Digitalization can be defined as reconstructing business models and organization to benefit from the use of digital technologies. Adaptation of digital technologies can also help organizations create unique value within the sector (Jeansson and Bredmar, 2019). However, adaptation to this transformation requires overcoming various barriers, such as lack of education, cyber threats, existing habits, lack of capital, and the multi-actor structure of maritime transportation (Raza *et al.,* 2023). Other potential barriers include information security concerns, lack of trust, and legal regulations. Nevertheless, digitalization has become one of the most important tools for firms to gain competitive advantage (Balcı, 2021).

Ports are a critical component and end point in maritime shipping to transport cargoes from one point to another point. Ports are also connection nodes for transshipment of goods. (Carbone and Martino, 2003; Wan *et al.,* 2021). In recent years, digitalization has become nearly the most important component of the port business sector following the introduction of many different port-related technologies. Of these, the Maritime Single Window (MSW) is a vital reporting and information exchange platform for maritime shipping. Based on a unified standard for ship arrival, stay, and departure, this system provides an efficient electronic reporting process that simplifies the clearance of vessels, cargo, crew, and passengers. The system's main goals simplification, standardization, harmonization, and transparency stem from the IMO FAL Convention, which aims to reduce bureaucracy, ensure secure and faster cargo delivery with lower transaction costs, and support fairer and more sustainable logistics (Peynirci, 2023).

Another important component of port digitalization is the Port Community System (PCS), which is widely acknowledged as a pivotal instrument in the development of seaports. PCS facilitates secure and intelligent information exchange between public and private port users, thereby supporting more sustainable business practices. PCS functions as a real-time, flexible, and complex information system that enhances the efficiency of cargo processes, including ship loading/unloading and customs clearance, both within the confines of the port terminal and in external environments. Greater collaboration and integration among port and supply chain stakeholders have been demonstrated to increase the sustainability of ports and supply chains. However, given that the objectives of port stakeholders frequently diverge, it is conceivable that a proportion of stakeholders may be reluctant to adopt PCS. Nevertheless, it has already been adopted by a

significant number of major ports, including Rotterdam, Amsterdam, Antwerp, Zeebrugge, Wilhelmshaven, Bremerhaven, and Hamburg (Tijan *et al.,* 2021b).

Here, it should be noted that there is a positive relationship between a country's level of development and the integration of technological systems into its ports. More specifically, developed countries may find it easier to adopt new technologies, particularly due to their advantage regarding investment costs. This transition may also be compromised by factors endangering the corporate structure, including cyber threats and information security.

In addition to technological systems, ports also use Industry 4.0 technologies, particularly internet of things-based automated guided vehicles (AGVs), automated stacking cranes (ASCs), automated quay cranes, and autonomous forklifts and reach stackers. This equipment enables efficient, autonomous, unmanned, and uninterrupted loading and unloading operations at ports (Martín-Soberón *et al.,* 2014).

Given the fast-paced evolution of technology, such innovations can be frequently renewed and their influence substantially amplified. Therefore, mapping the relevant literature and identifying emerging trends regarding technology acceptance in ports is essential for guiding both future research and practical implementations. Technology acceptance, which was first introduced to the literature by Davis (1989), explains how people or organizations accept or use new technologies. The theory provides a model to explain the acceptance or rejection of using new technologies in business models. Current studies have focused on specific port technologies and have left the task of providing a general framework to future studies. To fill this gap, this study develops a holistic framework to understand the nature of accepted technologies by examining the related literature. The study addresses the following two research questions:

1- What are the current research trends regarding technology acceptance in the port business?
2- What research questions should be addressed in future regarding port digitalization?

To this end, keyword analysis and bibliographic coupling were conducted through the VOSviewer software. The findings enabled the identification of overarching research patterns and thematic clusters within the literature. Based on these results, the study makes recommendations to inform future research directions.

The rest of the paper is structured as follows: Section 2 explains the methodology; Section 3 presents the analysis; Section 4 explains the findings and makes research recommendations; Section 5 concludes.

2. METHODOLOGY

A comprehensive review of the port digitalization literature was conducted in several phases. First, the databases for collecting papers were chosen. Bibliometric literature reviews typically rely on Scopus and Web of Science (WoS) databases, so the two databases were comprehensively evaluated to ascertain the optimal choice. While both databases had similar content, Scopus had more articles, so it was selected as the primary source for revealing port digitalization trends in the literature (Mollaoglu *et al.,* 2023).

Second, to obtain relevant articles, the following Boolean keyword search was conducted: "maritime" [and] "port" [and] "digitalization". No restrictions were imposed on year of publication. The sole restriction was that the language was stipulated as English. It is evident that articles in languages other than English (such as, Italian and Spanish) were not included. of the search identified 155 potential articles for review.

Third, bibliographic coupling analysis was then performed to obtain the VOSviewer output. A minimum citation threshold of five was implemented to ensure a more comprehensive representation of the studies. Having a minimum of 5 citations can provides evidence that the examined studies examined are more comprehensive and accessible. This restriction yielded 58 studies. There were no restrictions on type of study (e.g., book chapters and conference papers).

For the next phase, the study used VOSviewer

software. Developed by van Eck and Waltman (2009), this is a specialised software for visualising the scientific landscape within bibliometric studies, which accepts raw data obtained from the Scopus database. A significant strength of the software in comparison to other bibliometric tools is that VOSviewer can represent bibliometric networks graphically by generating clear and comprehensive visualisations of extensive datasets. This enables researchers to identify and categorize related fields of literature, identify research gaps, and reveal potential avenues for future investigation. Many different studies in maritime business have used VOSviewer to reveal current scientific trends, such as maritime security policy, maritime tourism, the circular economy, and sustainability in maritime studies, Industry 4.0 research, and sustainable development goals in maritime transportation (Kismartini *et al.,* 2024; Mollaoglu *et al.,* 2024; Razmjooei *et al.,* 2023, 2024; Selvaduray *et al.,* 2023).

VOSviewer was considered essential for this study's comprehensive review, given its extensive previous application in the literature and its capacity to explore specific bibliometric linkages. The analysis followed several steps. First, a keyword analysis was conducted to identify the fundamental terms underpinning the literature. This provided preliminary insights into the prevailing research directions and emergent trends. A country analysis was then conducted to determine the current heat map of studies for country separation. In the second phase, bibliographic coupling analysis was conducted to further examine the interconnections among studies and identify the key themes and subject areas through which port digitalization has been explored. The following section reports the analysis results of the keyword and bibliographic coupling in detail.

3. RESULTS

As explained above, a two-stage analysis was conducted to reveal trends in the literature regarding port digitalization. Section 3.1 reports the keyword and country analysis results to explore the current terms and country heat map. Section 3.2 reports the bibliographic coupling analysis results to reveal current research trends in port digitalization.

3.1. Country and Keyword Analysis

A country heat map analysis was conducted to identify relationships between countries and port digitalization. Figure 1 shows the country heat map analysis from the literature review while Figure 2 shows the number of publications related to the ten most-frequently studied countries.

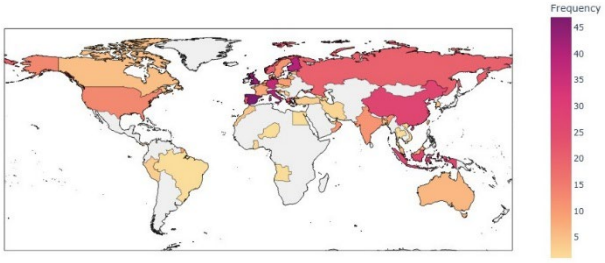


Figure 1: Country heat map analysis

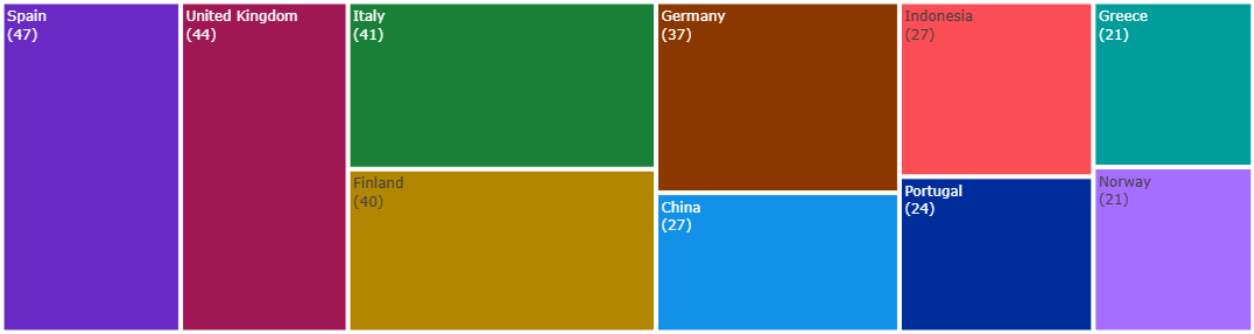


Figure 2. Number of publications regarding selected countries

Figures 1 and 2 indicate that European countries heavily emphasize port digitalization by conducting research, while Asian countries have also provided valuable insights for the literature with 20-25 studies. Considering the relevant literature and recent advancements in the field, there appears to be a correlation between the degree of digital integration within a country's port infrastructure and the volume of academic research conducted about the country's respective region.

Figure 3 presents the results of the keyword analysis. In the figure, some synonyms are presented as one word (e.g., "digitalisation" and "digitalization"; "maritime logistic" and "maritime logistics").

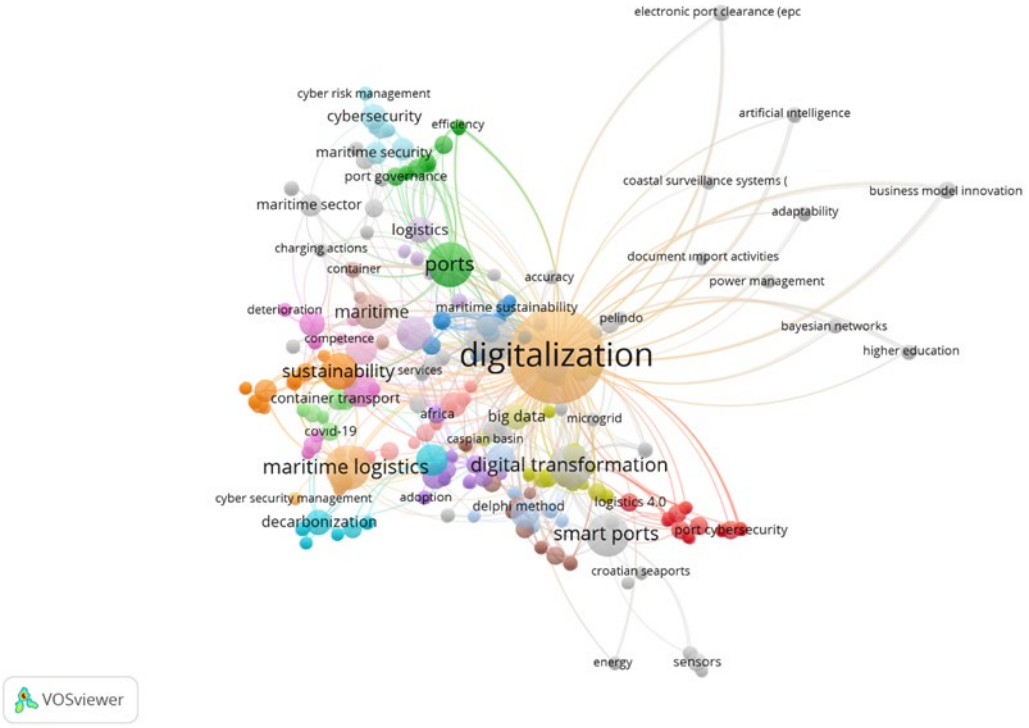


Figure 3: Keyword analysis

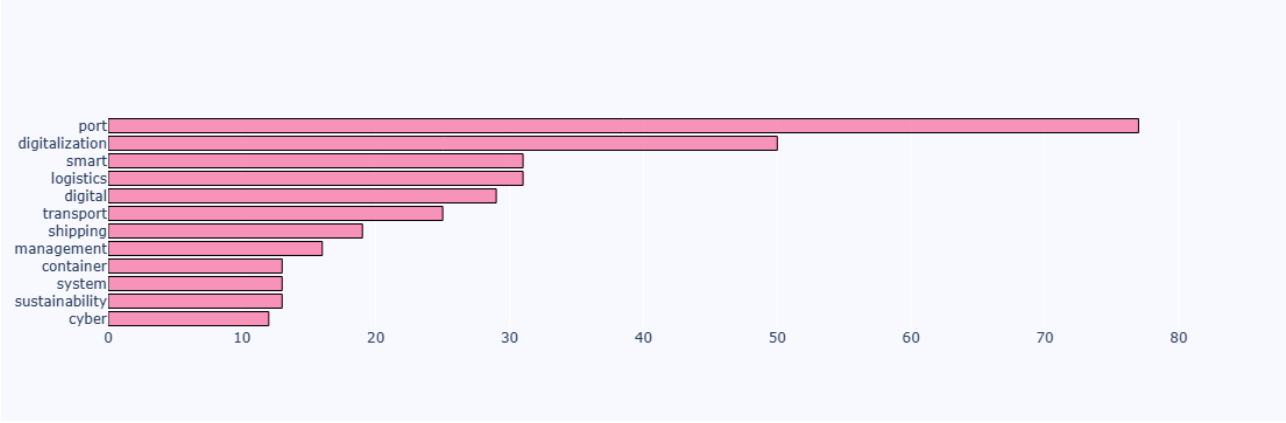


Figure 4. Most frequently used keywords

Figures 3 and 4 present the results of the keyword analysis of the port digitalization literature. The results indicate that the keywords can be interpreted from different perspectives within the thematic context.

More specifically, there appear to be two main

themes: digital technologies and decarbonization. Regarding digital technologies, the keyword "big data" was prominent within the Industry 4.0 paradigm. Meanwhile, concepts like smart ports, Logistics 4.0, and digitization of documentation processes were linked with digital technologies. Apart from concepts like digital technologies and integration, a significant emerging concept in the literature is cybersecurity. Indeed, the integration of digital technologies means that cybersecurity must remain a paramount concern and integration should be undertaken with this imperative in mind.

Decarbonization and sustainable technologies are also frequently used keywords alongside digital technologies, which suggests that they are gaining prominence in relation to digitalization.

3.2. Bibliographic Coupling Analysis

Bibliographic coupling analysis of the related literature was conducted to explore the current research trends regarding port digitalization. Bibliographic coupling occurs when two documents cite the same source. The underlying assumption is that if both documents reference a common work, they share a strong relationship and therefore should be grouped within the same cluster in visualization maps (Mollaoglu *et al.,* 2023; Small and Koenig, 1977). As explained earlier, for the present study, a minimum of five citations in the Scopus database was required to select the more influential and academically prevalent studies. Consequently, a comprehensive examination of 58 studies was undertaken to address the knowledge gap. The VOSviewer analysis indicated four clusters (see Figure 5). The following sub-sections explain the results in more detail.

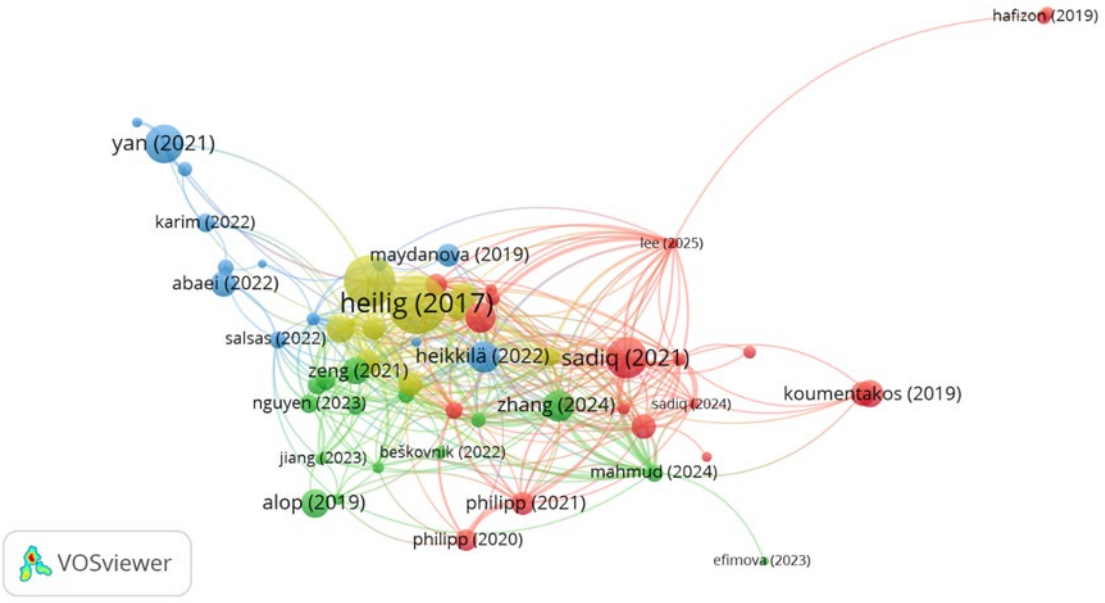


Figure 5: Bibliographic coupling analysis results

3.2.1. Cluster A

As Figure 5 shows, the studies in Cluster A, denoted in red, are not uniformly distributed. While one subset is positioned centrally within the cluster, others are located on the periphery. From the initial total of 20 studies in this cluster, a detailed examination led to the exclusion of three due to their limited relevance to the core topic. Consequently, a comprehensive review and thematic analysis were conducted on the remaining 17 studies.

A few studies focused on the smart port concept. Xiao *et al.* (2022) used the smart maritime index system to demonstrate the degree to which companies and ports are prepared for digitalization. Within this framework, smart ports were identified as a fundamental element in the creation of smart maritime shipping. Belmoukari *et al.* (2023) conducted a systematic literature review of studies of the smart port concept and identified several key concepts, such as automation, energy efficiency, operational efficiency, and innovative and smart technologies. Lee *et al.* (2025) discussed the changes and transformation of sixth-generation port logistics following the Covid-19 pandemic. They argued that the integration of technologies like blockchain, artificial intelligence, cloud systems, and the internet of things significantly impacted this transformation. Lastly, Philipp *et al.* (2021) studied the Port of Wismar, Germany, focusing on sustainable and autonomous practices in bulk cargo handling. Their findings highlighted that the smart port concept is feasible and that, from an environmental standpoint, its adoption could lower carbon emissions and waste. In addition, the integration of technological innovations was shown to shorten loading and unloading times, enhance operational efficiency, and reduce related costs.

Another important issue in Cluster A studies was decarbonization. Agarwala *et al.* (2021) investigated the role and effects of digitalization in maritime transport on decarbonization. They found that the use of widespread, advanced and accepted technologies in the sector supports decarbonization. Sadiq *et al.* (2021) comprehensively examined new infrastructure challenges and energy efficiency measures shaping the eco-friendly ports of the future. They revealed that the use of renewable energy, digitalization, and automation play a critical role in reducing the environmental impact of port operations. Consequently, they argue that, in order to achieve sustainability goals, ports must both embrace technological innovations and develop coherent strategies at the policy and management levels. Sarantakos *et al.* (2023) examined how digitalization can reduce carbon emissions, operating costs, and infrastructure investments at the Port of Tyne, UK. Their findings indicated that emission reduction technologies (shore power, equipment electrification, renewable energy, and storage) could reduce emissions by 93 per cent by 2040, while coordinated optimization of assets could yield 45 per cent energy cost savings by 2050. Bali *et al.* (2022) evaluated renewable energy options for ports. Focusing on the concept of smart and sustainable ports, Clemente *et al.* (2023) showed that ports can adapt to digitalization through automation, real-time and instant management, connectivity and accessibility control. They also reported that renewable energy use has gained significant importance regarding sustainability. Finally, Philipp (2020) examined the use of biogas in ports and its environmental impacts. They found that the supply of biogas in relation to blockchain and smart contracts is important for optimizing operational processes.

Cluster A studies also focused on digital technologies in port businesses. Costa *et al.* (2021) concluded that big data, the internet of things, artificial intelligence, and other forms of smart technology methods may help to improve performance and economic competitiveness, as well as port environmental sustainability. Meyer *et al.* (2021) concluded that blockchain technology, by fostering greater digitalization, can enhance port capacities and improve their transportation, environmental, and economic performance.

Other studies have introduced specific digital technologies and initiatives. Tsiulin *et al.* (2020) conceptually compared Port Community System (PCS) and blockchain-based scenarios for maritime document management. They concluded that both approaches share similar objectives, such as accelerating communication,

ensuring data security, and eliminating central intermediaries, but that while PCS relies on a centralized structure, blockchain offers a decentralized and transparent architecture. Thus, blockchain technology can provide a more effective solution to the problems that PCS aims to solve by enabling point-to-point communication between stakeholders without requiring trust. Suvadarshini and Dandapat (2022) presented the PortXchange platform developed by the Port of Rotterdam, Holland, which offers a standardized data-sharing solution for digitizing and optimizing port call operations. Their pilot study demonstrated that the platform reduced vessel waiting times from an average of 47 to 32 minutes and increased operational efficiency. As a result, PortXchange saved on fuel costs, reduced CO_2 and NOx emissions, and provided operational transparency for all stakeholders. Hafizon *et al.* (2019) proposed a concept called "E-Toll Laut" a blockchain-based e-government solution for Indonesian ports for ships whose dwell time exceeds four days. This system aims to improve port management by increasing accountability, simplifying monitoring processes, and expediting bureaucratic procedures.

Several studies investigated container booking and slot allocation optimization. Merino *et al.* (2022) developed a multi-agent-based framework to manage container reservations and slot allocations in maritime transport, aiming to optimize carrier-shipper interactions under uncertainty. The proposed system improves resource utilization through real-time information sharing and flexible decision-making processes. The results demonstrated that the approach is effective in increasing operational efficiency and ensuring a more balanced slot distribution. Finally, Mandal *et al.* (2024) proposed a multi-agent-based framework for container booking and slot allocation in maritime shipping in order to optimize the interaction between carriers and shippers and increase resource utilization by taking into account uncertainties and dynamic conditions.

In summary, Cluster A studies primarily focus on the interconnected concepts of smart ports, decarbonization, and renewable energy sources.

3.2.2. Cluster B

Cluster B, indicated in green, is located at the center of Figure 5. This cluster is strongly connected to other clusters, especially Cluster D (yellow). Examination of the 15 studies Cluster B indicated that one study should be excluded. Consequently, a detailed examination of 14 studies in Cluster B was conducted.

The cluster includes two comprehensive review studies of green ports, of which Jugović *et al.* (2022) focused on establishing green port governance models. The review indicated that decarbonization, digitalization, and multimodality are important for port sustainability, highlighting the need for holistic, context-sensitive governance models toward sustainable transitions. Zhang *et al.* (2024) focused on digitalization issues of green ports. The review indicated that digitalization enables real time monitoring and intelligent management of systems, while one of the most important enablers of the green transformation is digital innovation.

On the other side of Cluster B, there were several case studies of digitalization. Utama *et al.* (2024) employed a case study to develop the maturity model for digitalization by exploring the challenges that Indonesian ports face, such as adoption and integration of technologies. Focusing on Busan Port, South Korea, Seo *et al.* (2023) evaluated digitalization strategies in container shipping using multi-criteria decision-making methods. The most important main criteria were reliability and responsiveness while data accuracy and data consistency were the most important sub-criteria. identified four alternatives: traditional systems, data key integration, data accuracy improvement, and adoption of open platforms. Using the AHP-Fuzzy AHP and Fuzzy TOPSIS hybrid methods, they showed that the highest priority alternative strategy was improving data accuracy, followed by merging data keys, traditional systems, and adopting open platforms. Likewise, Mahmud *et al.* (2024) evaluated green port management practices in terms of sustainable operations for Asian ports. They found that Singapore has the industry's highest green port implementation and that pollution precautions are the most significant driver in the industry. Focusing on Taiwan, Yang

and Lin (2024) showed that digitalization drives to enhance organizational performance. Their study clarifies that the direct adoption of digital logistics platforms, however, does not yet yield a major performance impact. Lastly, Beškovnik *et al.* (2022) investigated the impact of the Covid-19 pandemic on the sustainable operation of port logistics in the Northern Adriatic region. The results revealed severe economic disruptions, including extreme increases in maritime transport prices and increased supply chain delivery times, while environmental sustainability was deprioritized in favor of reliability and cost. They found that logistics service providers adapted through significant social changes, such as implementing remote work (adopted by 74% of firms) and increasing investments in digitalizing operational processes. Seven studies in Cluster B formed a sub-cluster for dealing with port digitalization. Alop (2019) identified key barriers to implementing smart shipping applications, categorizing the most significant challenges as human factors, the unreadiness of complex systems, and external factors. Similarly, Nguyen *et al.* (2023) focused on adoption of blockchain technology in container shipping. They identified various barriers and approaches to adapting to blockchain technology by terminal operators, line operators, and freight forwarders, and made several recommendations. The most prominent barriers they identified included insufficient resources and needs, a lack of trust and expertise, privacy concerns, government support, and technological complexity. They proposed six key recommendations regarding blockchain adoption: focusing on sustainable applications; ensuring compliance in a phased manner through official development channels; progressing towards digitalization based on standardization; facilitating legalization and certification of blockchain-based solutions; and evaluating blockchain-based solutions against operational risks and disruptive events. Focusing on maritime container logistics, Wohlleber *et al.* (2022) argued that critical components for implementing digitalization include prioritizing strategic agility, fostering innovation ecosystems, and restructuring organizations. Fedi *et al.* (2019) took a different perspective by examining legal aspects, particularly how digital technologies can help ensure legal compliance of digital information technologies. They emphasized the positive impact of the implemented port community system and verified gross mass application on data flow, compliance with new regulations, and the regular functioning of communication channels. Jiang *et al.* (2023) examined the effects of port-centred information integration technologies on port performance. They found that digital technologies are currently reshaping the maritime industry and could transform it further in future. They used structural equation modelling to identify two primary direct and indirect factors. Regarding the indirect effect, they argued that port performance can be enhanced through information integration. Regarding the direct effect, they found that innovative use of information integration can lead to new, radical ideas, the emergence of new business models, and the creation of an environment for transformative change. Zeng *et al.* (2021) showed that internal organizational adaptation to electronic booking systems in the maritime supply chain is significantly influenced by coercive pressures from stakeholders and leading firms, as well as corporate compliance mechanisms. Lastly, Efimova and Saini (2023) investigated how digital technologies are connected with emission reduction and fuel consumption. They showed that active use of real-time automatic monitoring systems from application-oriented digital systems in ports can reduce emissions and fuel consumption.

In sum, Cluster B studies comprise green port reviews, digitalization case studies, and digital technologies at ports. This literature indicates that ports are also key sites for decarbonizing maritime transportation.

3.2.3. Cluster C

Cluster C (blue), located in the left center of Figure 5, comprised 13 studies. However, two papers were excluded from the cluster as irrelevant. Studies in this cluster focus on port and ship automation, digital security, and digital initiatives.

Regarding port and ship automation, Abaei *et al.* (2022) analyzed a real case to reveal the

unattended flexibility and resilience of the engine room in autonomous ships. Heikkilä *et al.* (2022) showed that container ports should focus on three main themes within the smart port concept: automation, sustainability, and collaboration. Yang and Hsieh (2024) evaluated the postCovid-19 perspective on port digitalization, particularly the critical success factors of port digitalization development in this era. They concluded that carbon emissions management and enhancing port safety were the most prioritized criteria for the maritime supply chain.

Several studies focused on digital security and legal perspectives. Karim (2022) found that the IMO's current legal frameworks are not adequate for ensuring cybersecurity, and investigated potential further reforms to deal with these threats. Focusing on Africa, Olapoju (2023) investigated the relation between cyber-crimes and port operations and automation to identify several key challenges. The results indicated that the key challenges to complying with digitalization were Africa's trade level, infrastructural development, piracy, and cyber-crimes. Lastly, Mohsendokht *et al.* (2024) developed a data-driven Bayesian network model to analyze maritime cybersecurity risks, using two decades of historical incident data. The results identified ransomware as the most frequent cyber threat, accounting for nearly 25% of incidents, particularly targeting shipping companies and seaports. They highlighted the significant influence of temporal factors, victim countries, and target types on attack patterns. The validated model demonstrated high accuracy and provided actionable insights for enhancing cybersecurity measures in the maritime industry.

The final subgroup in Cluster B concerned digital initiatives for port operations. Using machine and deep learning methods for the first time in this field, Yan *et al.* (2021) conducted a comprehensive review of emerging approaches within maritime transportation research. Fahim *et al.* (2021) defined the first physical internet concept, namely as a global logistics system that enables seamless information sharing through various standard interfaces and protocols. They examined the integration of the physical internet concept with ports and its readiness for the future. The findings showed that the development of transportation infrastructure, standardization, terminal area and hinterland development, information systems integration, and sustainable management are essential for developing the physical internet concept and integrating it into ports. Valero *et al.* (2022) conducted prediction analysis on estimated time of arrival for container ships. Garrido Salsas *et al.* (2021) identified the future role of ports by considering several emerging trends, particularly renewable energy, digital technologies, big data and artificial intelligence. Lastly, Heikkilä *et al.* (2024) identified and defined the concept of smart fairways, outlining five foundational elements (e.g., Communication Systems) and ten advanced services (e.g., Remote Pilotage and Enhanced VTS) essential for modernizing maritime infrastructure. A key finding is that robust communication systems are critical because they enable the development and integration of more advanced services. Heikkilä *et al.* argued that these elements are interdependent and must be developed in a coordinated, phased manner to enhance maritime safety, efficiency, and environmental sustainability.

In summary, Cluster B studies evaluated port and ship automation, digital security, and digital initiatives. Their findings indicate that initiating more digital start-ups or technologies provides ports with more efficient and transparent processes.

3.2.4. Cluster D

Cluster D (yellow), located in the center of Figure 5, comprised 10 studies, that examined below.

Four studies investigated the potential barriers to adopting digitalization. Heilig *et al.* (2017) showed that coordination and collaboration were potential barriers. Brunila *et al.* (2021) investigated the potential disadvantages of port digitalization, finding that important factors were interoperability and stakeholder interaction between parties involved in port logistics. Jović *et al.* (2019) also found that system integration and stakeholder connectivity were important for digitalization. They suggested developing a port community system and national single window. Jović *et al.* (2022) investigated the determinants

of adapting to digitalization in the maritime sector, finding that organizational, environmental, and technological dimensions play significant roles in shaping this process. They also concluded that digitalization can drive fundamental shifts in existing business models.

The other six studies in Cluster D investigated current digitalization situations. Within this subgroup, three studies conducted comprehensive literature reviews. Sanchez-Gonzalez *et al.* (2019) examined the applications of 10 components (autonomous vehicles, artificial intelligence, big data, virtual reality, augmented and mixed reality, the internet of things, cloud computing, digital security, 3D printers, and additive manufacturing) in the maritime sector, both in port and transportation contexts. They found that the most studied topics were autonomous vehicles, artificial intelligence, and big data analysis, whereas research into cloud computing, 3D printers, and security issues needed further development. Lange and Grafelmann (2022) conducted a comprehensive systematic review of the digitalization of maritime logistics systems by analyzing 37 studies published between 2010 and 2021. Their findings indicate substantial heterogeneity in the extent of digital adoption across ports and supply chain stakeholders. The reviewed studies also indicated that while digitalization offers notable efficiency and sustainability benefits, persistent challenges related to data sharing and stakeholder collaboration remain critical barriers. Neugebauer *et al.* (2024) examined digital twins at seaports based on reviews and case studies. Their findings highlighted issues such as lack of standardization, problems related to incorrect or excessive use of the concept, and areas that need to be researched in the future. They concluded that digital twins offer significant opportunities in terms of transparency, data-driven decision-making, and operational optimization, but that various challenges in implementation and integration remain.

The other three studies in this sub-cluster evaluated the current situation through case studies. Zerbino *et al.* (2019) found that digitalization has accelerated the flow of information and documentation and made it more efficient. Their study of Mediterranean ports showed that digital data flow to stakeholders increased efficiency in operational processes. González-Cancelas (2020) showed that Spanish ports remain at an intermediate stage in their digitalization journey, indicating considerable potential for further development. González-Cancelas concluded that ports cannot achieve digitalization solely by adopting technology; rather, successful implementation requires the integration of all stakeholders across the transport chain. Lastly, Paulauskas *et al.* (2021) provides broader perspective on such cases by developing a methodology to assess the level of digitalization in ports. Using their proposed mathematical model, they examined case studies of 30 ports located in the Baltic Sea, North Sea, and Mediterranean, which they ranked in terms of digitalization levels. By comparing ports grouped as small, medium-sized, and large, they estimated that large ports had achieved approximately 30% more digitalization than small and medium-sized ports.

In sum, Cluster D studies demonstrate the challenges and barriers of digitalization and the current state of digitalization in ports.

4. DISCUSSION AND FUTURE RESEARCH RECOMMENDATIONS

In this study, 58 papers related to port digitalization were comprehensively reviewed. The studies fell into four main groups, which could be further subdivided into subgroups based on their topics.

Cluster A was heavily related with the concepts of smart ports, decarbonization of shipping and ports, and alternative, renewable energy sources, and digital initiatives. Future research can focus on more comparative studies on smart ports and smart shipping. Furthermore, based on the reviewed literature, analyses of alternative fuels and their costs can be deepened by including case studies. Alternative fuels, including selection processes, can also be examined more deeply. Finally, future studies can also investigate adaptation to newly introduced digital technologies.

The studies reviewed in Cluster B examined the green port reviews and digitalization of case studies. Future studies can compare case studies

and evaluate the differences between them. Review studies can also be highly integrated with digitalization with green transformation. Multi-criteria decision making, structural equation modelling methods should also be integrated and enhanced with the digitalization and decarbonization studies of port logistics. Finally, future studies can conduct more detailed cost-benefit analyses of decarbonization initiatives.

The studies in Cluster C related to automation of the port and shipping, digital security, and port business initiatives. In future mixed-methods studies can help understand how to overcome the difficulties in preventing cyber-crime in the shipping sector. In addition, comprehensive review studies on cyber security can improve our understanding of the current situation.

Cluster D studies focused on the challenges and barriers of digitalization. Future studies can examine these challenges and barriers more deeply by considering cases and regional differences. Methodologically, they can prioritize multi-criteria decision-making methods or cause-effect analysis using DEMATEL. In addition, it may be useful to evaluate these barriers using fuzzy logics to avoid the sharp judgements of experts.

The present study provided a general perspective on port digitalization, the current state of digital technologies, and their widespread use. From a theoretical standpoint, the study offers a general perspective on the literature of port digitalization and makes recommendations for future research in this context. Consequently, its findings may provide a valuable resource for future research endeavours. Practitioners also stand to benefit from the study's insights into contemporary technologies and prospective future advancements in port development.

5. CONCLUSION

This study provides a comprehensive review to reveal current research trends and future research opportunities regarding port digitalization. To do so, a country heat map was first developed to visualize the geographical distribution of research activity. Second, the data were analyzed to identify the countries demonstrating the most significant interest in port digitalization. Third, a keyword analysis was performed to identify the most frequently used terms in the reviewed studies. This showed that digital technologies and sustainability concepts are of primary importance. Fourth, a bibliographic coupling analysis was performed to reveal the general trends in the literature. This showed that the reviewed studies fell into four main clusters. In general, the studies concentrated on digital technologies and initiatives, as well as sustainable and environmentally friendly applications. Based on the preceding analysis, a series of recommendations for future studies were made. Overall, this study provides a valuable opportunity for researchers to examine the concept of port digitalization and its current status in the literature.

There were also certain limitations in the study. First, the keyword search yielded results related only to the concepts of ports and digitalization. Second, the studies were obtained by searching only one databased, namely Scopus. Third, the study underrepresents certain geographic regions, especially considering the located geography of the researchers. Future studies could evaluate the literature from a more general perspective, taking into account digitalization in the maritime sector, while incorporation of more comprehensive databases could facilitate a more extensive examination of diverse perspectives and studies.

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Mahmut MOLLAOĞLU: Conceptualization, Investigation, Methodology, Software, Writing – original draft, Writing – review & editing. **Hakan DEMİREL:** Investigation, Writing – original draft, Writing – review & editing. **Muhammet GÜL:** Conceptualization, Writing – original draft, Writing – review & editing, Supervision.

CONFLICT OF INTEREST

The author(s) declare that for this article they have no actual, potential or perceived conflict of interests.

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