Drivers, Barriers, and Enablers of Digital Transformation in Maritime Ports Sector: A Review and Aggregate Conceptual Analysis

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Abstract. This paper develops a conceptual framework for digital transformation in the maritime ports sector. The study combines a systematic literature review and aggregate conceptual analysis to explicate drivers, barriers, and enablers of digital transformation. Our literature review is grounded in maritime ports' existing albeit scant empirical evidence. Our attempt bridges the existing gap in ports literature review that has included articles from sources outside the maritime industry's domain. We deploy aggregate conceptual analysis on 35 maritime port related empirical literature and rank emerging concepts with respect to digital transformation phenomenon. We then synthesize 32 concepts deemed essential for the effective implementation of digital transformation in the ports sector. In doing so, four thematic categories emerge: i) drivers, ii) barriers, iii) enablers, and iv) digital transformation idiosyncrasies in ports. In terms of contribution, this study is one of the earliest efforts to aggregate factors related to digital transformation in the maritime ports sector. Our findings provide actionable insights that enable managers of maritime ports, stakeholders, and policymakers to successfully navigate the digital transformation process. For researchers, directions for future research are offered.

Keywords: Digital transformation · Digital transformation dimensions · Literature review · Maritime ports

1 Introduction

Maritime ports are indispensable enablers of international freight transport and pivotal nodes in global supply chains. Being inextricably intertwined in national socio-economic and geo-political systems (Haraldson *et al.*, 2021; Inkinen *et al.*, 2021), ports face increasing pressure to evolve and pace up with relentless global dynamics (Ippoliti *et al.*, 2018; Wang and Sarkis, 2021). For instance, drivers like the desire to streamline the efficiency of ports processes and operations, sustainability pressures from domestic and international regulatory bodies such as IMO (Inkinen *et al.*, 2021; Lee *et al.*, 2019; UNCTAD, 2019), competitions across ports, and pressures from trading partners, push ports to redefine their business and engagement models (Gausdal *et al.*, 2018).

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Furthermore, the trends in shipping industry such as changes in the size and capacity of vessels warrant modern equipment at ports to streamline loading, offloading, and other related operations in the ports perimeter. Given the complexity of ports' operations and multiplicity of actors, the viable way for ports to adapt to global dynamics hinges on their ability and willingness to explore and exploit novel digital technological solutions. Indeed, the latter have increasingly become an imperative source of sustainability and competitive advantage (Heilig *et al*., 2017; Seo *et al*., 2023; Yusheng Zhou *et al*., 2023). For instance, ports of Hamburg in Germany and Gothenburg in Sweden have made significant strides in their digital transformation (DT) initiatives. Through the introduction of digital twin and the use of sensor technologies, the Port of Hamburg has been able to monitor on-ground operations including current conditions of major port infrastructure utilization real-time, thereby reducing potential downtime, and optimizing waiting times for vessels and trucks (HPA, 2023; Min, 2022; Molavi *et al*., 2020). Having learned the importance of attaining critical mass in achieving successful digital transforming, the port of Hamburg introduced homePORT digital initiative with the aim of involving port stakeholders in innovation co-creation (HPA, 2023). Likewise, the Port of Gothenburg through its Port Optimizer digital initiative has been able to integrate stakeholders' disparate data sources into a unique data source that helps the port, and its stakeholders address challenges such as data provenance and quality, and visibility of cargo in transit. This has enabled the Port to improve its productivity from ship to shore and terminal to hinterland customers (Dalaklis *et al*., 2022). Consequently, ports are increasingly under pressure to undertake DT as part of strategic readjustment and adaptation.

In ports' context, DT refers to a process where port organizations and their related ecosystems deliberately explore and exploit affordances of novel technologies such as cloud computing, sensors, internet of things (IoT), big data, artificial intelligence, virtual and augmented reality, cybersecurity, blockchain, and analytics among others, to reinforce their communication, connectivity, information capturing and sharing, and analytical capabilities; thus, adapting to relentless competitive dynamics (Baum-Talmor and Kitada, 2022; Gómez Díaz *et al*., 2023; Heikkilä *et al*., 2022; Lin, 2023; Min, 2022; Parola *et al*., 2020). The use of these novel technological solutions has enabled Ports of Rotterdam, Hamburg, and Quebec to transition into smart ports which are characterized by efficient use of port assets, intelligent port problem solving, and energy efficiency (Min, 2022; Molavi *et al*., 2020).

Unlike traditional IT systems, novel digital technologies pervade beyond individual organizational boundaries which complicates their adoptions as it pertains to accountability and economic rent distribution. Thus, the process of DT is regarded as disruptive because adopting novel technological solutions are not merely the end in itself, it pervades and warrants rethinking of several organizational aspects like business process, business model, structure, people, products and services, and engagement model (Raza *et al*., 2023; Tijan *et al*., 2021). It is for this reason that many port organizations grapple with successful implementation of DT initiatives. In fact, the pace at which ports uptake digital technologies is generally slow and fragmented (Heilig and Voß, 2017; Jović *et al*., 2022; Kapidani *et al*., 2020; Sanchez-Gonzalez *et al*., 2019; Tijan *et al*., 2021; Y. Zhou *et al*., 2020). Furthermore, the fragmentation of DT trajectories among ports is evidenced in contexts where only a fraction of ports such as Hamburg in Germany,

Singapore in Singapore, Antwerp in Belgium, Rotterdam in the Netherlands, Qingdao in China, Nagoya in Japan, Long beach in the United States, and Gothenburg in Sweden, to mention but a few, are actively involved in the adoption and exploitation of novel technological solutions. Examples of digitalization initiatives in these ports include: the application of mobile technology and wireless connectivity by the port of Singapore to streamline cargo flows efficiency, communication, and workforce satisfaction (Molavi *et al*., 2020); the use of OnTrack application by the port of Rotterdam, which has enabled it to improve the efficiency of the planning process and train scheduling prediction benefiting both railway operators, traction suppliers and hinterland water terminals (Karaś, 2020); and the use of *iNose* technology at the port of Antwerp which has enabled it to monitor air quality in the port given its high throughput of chemical cargos (Karaś, 2020). These ports have one thing in common – a relentless exploitation of novel technological solutions. On the contrary, about 80% of active maritime ports are still bogged down with rudimentary digital solutions such as spreadsheets and whiteboards in performing their daily operations (Heikkilä *et al*., 2022; Min, 2022), consequently defeating the efforts to address the mounting call for efficiency, safety and security.

In practice, many ports have been applying digital technologies for many years, i.e., terminal operating systems, port community systems, electronic data interchange (EDI), and RFID (Heilig and Voß, 2017) to develop for instance, traceability systems for maritime operations (Lin, 2023). However, latest technological breakthroughs, increase in global freight transport, and complexity in maritime supply chains, have rendered conventional ports digital systems inadequate (Seo *et al*., 2023). Given the mounting environmental dynamics such as the COVID -19 pandemic (Y. Zhou *et al*., 2020), there have been growing concerns on the slow acquisition of Industry 4.0 digital technologies which arguably exacerbates ports' inefficiencies and stifles their efficacy in facilitating efficient cargo flows and associated information through global supply chains (Dalaklis *et al*., 2022; Hsu *et al*., 2023). For instance, the ultra large container vessel is 24,000 TEUs strong and requires modern port equipment and streamlined operations across a range of port stakeholders. As central nodes with value added logistics, ports and their disparate stakeholders must synchronize their actions to effectuate meaningful value creation and capture (Heilig *et al*., 2017; Jeevan *et al*., 2020; Nikghadam *et al*., 2021).

Typically, port organizations and their stakeholders (i.e., customs, customs agents, shipping lines, shipping agents, clearing and freight forwarders, terminal operators, etc.) (Denktas-Sakar and Karatas-Cetin, 2012) hardly share common interests, similar management principles, and sets of behavior – a tendency that chokes concerted efforts to undertake DT unanimously (Carlan *et al*., 2017). For instance, Heilig *et al*. (2017) showcased how an innovative *SmartPORT* initiative at the port of Hamburg fell through due to lack of collaboration from the stakeholders. The authors insinuated that, for digital technologies to take root, important costs and benefits considerations must be made upfront and impact assessment be conducted to determine an appropriate way to reward different stakeholder groups based on their interests.

Similarly, the need to preserve information confidentiality as a means to expropriate value is not uncommon as evidenced by Zeng *et al*. (2020)'s empirical work that found out that freight forwarders refrained from using an open digital platform for container

bookings in that regard. While DT introduces transparency and visibility for orchestrators, it also jeopardizes the source of power inherent in asymmetrical information which other value chain actors leverage. Nevertheless, human and technical challenges to implementing DT initiatives go beyond a mere intent of acquiring novel technologies. Port organizations must holistically consider how such endeavors impact such aspects as strategy, scope, and (digital) leadership (Raza *et al*., 2023).

While extant literature abounds with studies on barriers, drivers, and success factors of DT (Brunila *et al*., 2021; Carlan *et al*., 2017; Tijan *et al*., 2021; Vairetti *et al*., 2019; Y. Zhou *et al*., 2020), there is a lack of exhaustive review and compilation of antecedents to DT in maritime ports sector. Although Tijan *et al*. (2021) attempted to conduct a literature review on barriers, drivers and success factors of DT in maritime transport sector, their analysis included studies that came from outside the field of maritime domain (i.e., manufacturing, automobile, and insurance sectors). Such analysis confounds the understanding of contextual factors only pertinent to maritime domain, and systemically precludes other scholars from building on it. A recent study by (Jović *et al*., 2022) also notes and underscores the drawback implicated in Tijan *et al*. (2021)'s work. As such, an extensive review that is exclusively based on the maritime sector is warranted. We therefore seek to bridge this gap by conducting a systematic literature review combining it with aggregate conceptual analysis (MacInnis, 2011). We then showcase peculiarities of undertaking DT in the face of multitude stakeholders and contextual dimensions and suggest a framework that provides a theoretical foundation and actionable managerial recommendations.

The remainder of this paper is articulated as follows: Sect. 2 describes a systematic literature review methodology. Section 3 presents the findings and synthesis. Section 4 places the results in perspective and provides actionable managerial and policy implications. Section 5 concludes the paper and outlines directions for further research.

2 Literature Review Methodology

This literature review aims to unearth the current state and trends of DT in maritime ports sector using context-specific empirical literature. To ensure the reliability and validity of our results, we adopted a rigorous and structured approach in accordance with (Tranfield *et al*., 2003). Thus, this study deploys a three-phase approach to perform a content analysis of literature on DT in maritime ports. Phases 1 and 2 are described in Sect. 2, whereas Phase 3 is presented in Sect. 3. In the first phase, we identified a corpus of articles using specific keywords search strategy (see Fig. 1). In the second phase, we coded the content of the articles to extract important emerging concepts deemed pertinent to DT in maritime ports. Subsequently, we constructed a network analysis to determine the relationships between the concepts and their relative importance. In the third phase, following aggregation approach (MacInnis, 2011), we synthesized the concepts and developed a conceptual framework. These steps are detailed in the subsections that follow.

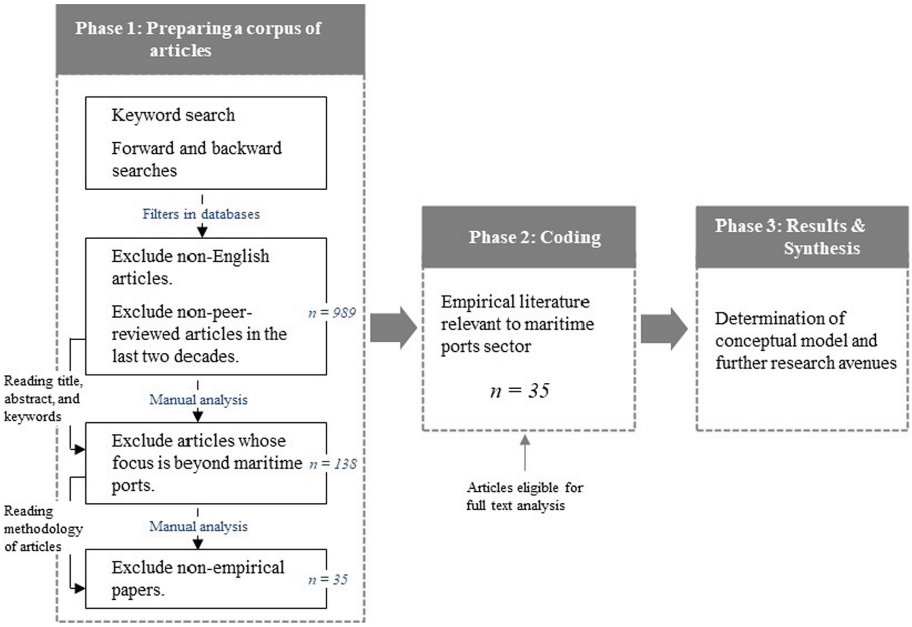

Fig. 1. Review methodology of this study. Source: Authors' own elaboration as adapted from (Tranfield *et al*., 2003).

2.1 Phase 1: Preparing a Corpus of Articles

The articles search exercise commenced with inclusion and exclusion criteria focusing on specific keywords. We limited our search criteria to open access, peer-reviewed empirical academic articles on DT in the maritime ports from 2000 to February 2023. The inclusion criteria were formulated following the recommendations by (McWilliams *et al*., 2005). Indeed, we resorted to including only peer-reviewed journal articles as these demonstrate rigor in quality assurance mechanisms and therefore, have a significant impact on new knowledge (Arduini and Zanfei, 2014; McWilliams *et al*., 2005). Since non-english academic articles tend to have limited contribution to the international academic discourse, we excluded them in accordance with (Boselie *et al*., 2005).

In line with Tranfield *et al*. (2003), we used "digital transformation" AND "maritime ports" as key search terms within title, abstract, keywords or full text from Science direct, Sage, ProQuest, Elsevier, Google Scholar, Web of Science, Semantic Scholar, and Research Gate databases using the filters we have described above. To broaden our search strategy, we extended the keyword combinations to phrases; "digitalization of maritime ports", "digitalization" OR "maritime business". Other synonyms of maritime ports such as "shipping ports", "maritime logistics", "maritime business", "maritime supply chains", "shipping industry", "smart ports", and "maritime sector" were alternatively used in the initial searching exercise. Additionally, variants "digitalization", "digitization", and "digitisation" were used. Furthermore, we performed backward and forward searches to expand the scope of relevant literature.

Eventually, we retrieved 989 papers between March 11, 2021, and February 20, 2023. After manually removing duplicates and reading through titles, abstracts, and keywords, we narrowed the list down to 138 articles. At this stage, we considered an article to be relevant if it addressed DT in the maritime ports' context. Furthermore, central to this study's interest in empirical research work, we developed a final list of 35 peer-reviewed articles having read through the methodological choices of the articles in the preceding step as shown in Fig. 1. The 35 articles were further analyzed by fully examining their text.

2.2 Description of Reviewed Articles

After reading all 35 empirical papers in full, we generated an overview of their contributions in terms of context, methodology, and trend as depicted in Table 1 and Fig. 2.

Table 1. An overview of empirical contributions in terms of context, methodology

Methods/Context	Africa	America	Asia	Australia	Europe
Case study	(Gekara and Nguyen, 2020)		(Lambrou *et al.*, 2019; Zeng *et al.*, 2020)		(Bisogno, 2015; Fedi *et al.*, 2019; Gausdal *et al.*, 2018; Inkinen *et al.*, 2019, 2021; Philipp *et al.*, 2019; Raza *et al.*, 2023)
Mathematical modelling approach		(Molavi *et al.*, 2020)	(Chowdhury *et al.*, 2023; Hsu *et al.*, 2023; Kashav *et al.*, 2022; Seo *et al.*, 2023; Zhou *et al.*, 2020)		(Carlan *et al.*, 2017; Zhang and Lam, 2019)
Mixed methods		(Vairetti *et al.*, 2019)	(Iman *et al.*, 2022)		(Kapidani *et al.*, 2020; Philipp, 2020)
Others					(Bauk *et al.*, 2017; Bavassano *et al.*, 2020; Camarero Orive *et al.*, 2020; Gómez Díaz *et al.*, 2023; González-Cancelas, Molina, *et al.*, 2020; González-Cancelas, Molina Serrano, *et al.*, 2020)
Survey			(He *et al.*, 2023; Kuo *et al.*, 2021; Lin, 2023; Yang, 2019)	(Djoumessi *et al.*, 2019; Gekara and Nguyen, 2018)	(Peynirci, 2021)
	(1) 3%	(2) 6%	(12) 34%	(2) 6%	(18) 51%

We can depict a lopsided distribution of empirical literature with European and Asiatic authors in the lead. These two regions accounted for 85% of all reviewed empirical papers. Africa had only one empirical work at the time of our review, below America and Australia which had two publications each. The three regions together scraped only 15% of the empirical work. In terms of methodological choices, we depict a diverse set of approaches the authors adopted across the regions. Case study has been the most utilized method and accounted for (11) 31.4% of the reviewed empirical research. This is perhaps justified by the novelty of DT phenomenon where researchers try to unravel its tenets. On the other hand, mathematical approaches such as analytical hierarchy process (AHP), fuzzy set qualitative comparative analysis (FsQCA), accounted for (8) 22.9% which also gives an indication of deliberate efforts to use expert opinions to understand the DT phenomenon better. About (4) 11% of the papers utilized mixed methods approach while (6) 17% deployed survey. Meanwhile, a myriad of other methods such as business observation tool (BOT), strengths, weaknesses, opportunities and threats (SWOT) accounted for (6) 17% of the reviewed papers.

With regard to the trend of publications over the past two decades, Fig. 2. Depicts that, the researchers in maritime domain only started to empirically measure the concept of DT in the European context in 2015. From then on, the trend of publications of empirical research on maritime industry's DT increased steadily and peaked in the year 2020 before the pandemic. According to our analysis, 23 empirical works had been conducted until then. The trend declined sharply with only 2 papers in 2021, presumably due to the pandemic and associated restrictions which might have precluded the traditional methods of collecting data. However, from 2022 to date, the trend has been rising again with about 10 papers published during this period possibly due to the normalization of human activities post-pandemic. Nevertheless, the trend depicts the scarcity of empirical literature on DT phenomenon and the pace at which academia is at odds with technological breakthroughs.

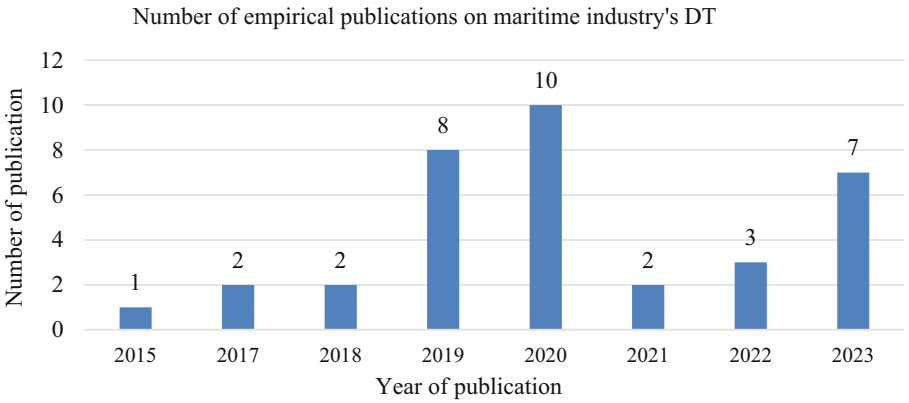

Fig. 2. Distribution of empirical papers on DT over the past two decades. Source: Authors' own elaboration from empirical literature review.

2.3 Phase 2: Coding Process

We read through the final list of 35 empirical peer-reviewed articles, in the process, jotting down all concepts that we deemed relevant to DT in maritime ports. We recorded these concepts with their respective authors in an excel spreadsheet. This exercise resulted in an initial list of 104 concepts. As each researcher coded the concepts independently, a consensus had to be reached and any disagreements resolved. Furthermore, in order to reduce the dimensions and duplications of concepts emerging in different articles, we aggregated all closely related concepts in accordance with (MacInnis, 2011) which resulted into 32 concepts that this study synthesized.

We then developed a network diagram to ascertain how these concepts related to each other. Firstly, we enumerated the concepts and respective authors in a fresh excel sheet, and then deployed a pivot table functionality to visualize and aggregate concepts co-occurrence with respect to each paper. The results of the pivot table enabled us to develop a weighted matrix of *nxm* dimensions, where n represented rows of 32 concepts, and m represented 35 papers. This matrix considered each concept against all others that have been mentioned by one paper for all papers.

Secondly, as we determined to use the *igraph* function in R software version 4.2.1, to generate network diagram of the concepts, we necessarily reduced the weighted concept matrix into a two-column matrix. For instance, agility co-occurred with other concepts in 33 articles 50 times, so we enumerated it fifty times against all co-occurring concepts. We repeated this exercise for all concepts in the weighted concept matrix and finally generated a 270x2 matrix that we fed into *igraph*. The outcome of this exercise is the network diagram which is illustrated in Fig. 3.

As shown in Fig. 3, the nodes of the network (in orange circles) represent 32 concepts while the arcs (connecting lines) represent interconnectedness amongst concepts. The numeric figures on the nodes were computed by an algorithm in *igraph* function in R-software and quantify the degree of centrality of each concept relative to others in the network. The degree of centrality indicates how important a concept is in a network (Q. Liu *et al*., 2022). The higher the degree of centrality the closer to the center of the network the concepts are located. In this study, centrality ranged from 16 to 31. Thus, the concepts that are closest to the center of the network indicate higher degrees of centrality (i.e., information sharing and digital literacy, to mention but a few), than concepts furthest from the center (i.e., coopetition). Noteworthy, some concepts i.e., digital platforms and investment cost demonstrated equal quantitative weights, however, they differ in terms of their degrees of centrality. The latter is located much closer to the center of the network and alludes to its relative importance than the former.

Furthermore, the network diagram serves an illustrative purpose that provides insights to practitioners i.e., port authorities, public authorities, and policy makers on aspects that require utmost urgency with respect to DT. Researchers can further operationalize the concepts and test the strength of associations of causal relationships by considering the most critical aspects as emerging in the network diagram. This can further enlighten our understanding of nuances these factors present thereby informing a better management of DT endeavors.

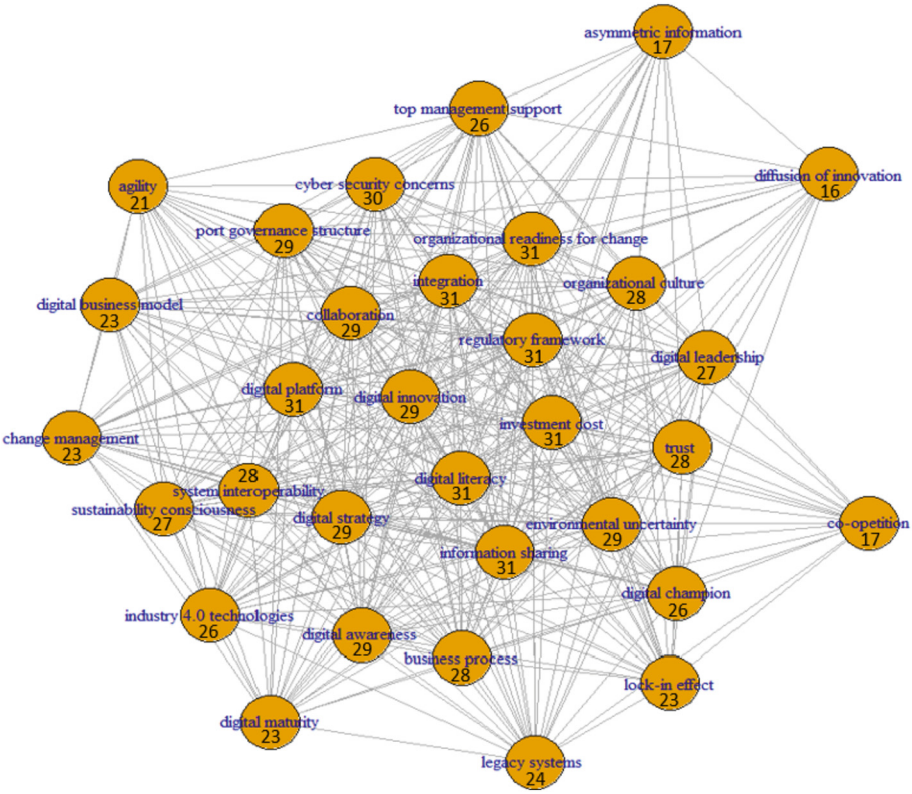

Fig. 3. Network diagram showing concepts' interrelationships and their centrality. Source: Authors' own elaboration from empirical literature review. (Color figure online)

3 Phase 3: Results and Synthesis

3.1 Drivers, Barriers, and Enablers of DT in Maritime Ports Sector

Based on our review of empirical peer-reviewed articles, we found that ports' DT is a function of many factors (i.e., the concepts in the network diagram) some of which exert opposing effects on implementation initiatives. We thematically aggregate these factors into drivers, barriers, and enablers, and provide anecdotal nuances of their interplays on maritime ports' DT. We started by computing the quartiles of the degrees of centrality and used them to categorize the concepts into high, medium, and low importance. The first group (high importance) consists of concepts whose degrees of centrality are equal to or above the third quartile. The second group (medium importance) consists of concepts whose degrees of centrality are above the first quartile and below the third quartile, while the last group consists of concepts whose degrees of centrality are equal to or less than the first quartile. The computation of quartiles of degree of centrality of each concepts permitted a more objective justification for our choice of explicating only selected factors in the proposed framework in Fig. 4. It also corroborates the visualized interrelationships

of factors in the network diagram as shown in thematic Table 2. Next, we discuss our findings as follows.

Drivers. We identified 3 major drivers that propel ports into undertaking DT as depicted in Table 2. The three drivers fall under high and medium degrees of centrality. Due to our perceived relevance of the drivers, we have explained all three. Therefore, the maritime port sector is increasingly under competitive, regulatory, and sustainability pressures. Being a value-adding logistic node in the global supply chain, ports strive to reconfigure their business processes to improve productivity (Gekara and Nguyen, 2020), reduce operational costs (Gausdal *et al*., 2018), improve efficiency and transparency of maritime business (Y. Zhou *et al*., 2020), better measure, monitor, and control port operations (Camarero Orive *et al*., 2020; Carlan *et al*., 2017; Gekara and Nguyen, 2018; González-Cancelas, Molina Serrano*, et al*., 2020), and optimize ports' infrastructural capacity usage (Carlan *et al*., 2017).

Nevertheless, ports must fulfil regulatory and sustainability requirements such as carbon neutrality (Inkinen *et al*., 2021), and continuous safety and security improvements (Bavassano *et al*., 2020; Camarero Orive *et al*., 2020; Carlan *et al*., 2017; Gausdal *et al*., 2018; Philipp, 2020). These forces are so imminent that ports turn to advanced digital technologies as the potential avenue for addressing such global dynamics (Chowdhury *et al*., 2023). However, we exercise caution in providing cursory generalization of the impact of the drivers across the board. We acknowledge that different ports may be subjected to disparate drivers at different temporal-spatial dimensions. For instance, we argue that ports may not be subjected to similar carbon neutrality requirements in a broader sense which may also differentiate how they adopt DT. Importantly, DT should be considered as a tool and not an end. This makes the need to unveil different ports' objective functions interesting. For instance, ports in developed world are more subjected to strict environmental preservation including containing negative social externalities, as such, modern technologies may be sought to address the need to comply to environmental sustainability requirements. Nevertheless, implementation of DT initiatives in ports is a function of a complex interplay of barriers and enablers as described underneath.

Barriers. We identified 14 barriers to successful implementation of DT in the ports sector (see Table 2). Based on their degree of centrality, only a few barriers have been discussed underneath.

Information Sharing. This has emerged as one of the serious most barrier to DT. Arguably, open information sharing accelerates perceived infiltration of trade secrets and loss of power among stakeholders due to information dis-intermediation (Raza *et al*., 2023; Zeng *et al*., 2020). Indeed, ports ecosystems are complicated by a myriad of actors who have disparate competitive goals and therefore succumb to potential opportunistic appropriation which may preclude stakeholders' trust in each other regarding information sharing (Bavassano *et al*., 2020). Some actors may express a low inclination to share correct information relating to their business model, business process, products and services, and customers engagement model fearing that, these can be used against them and thus reduce their competitive efficacy (Zhang and Lam, 2019). For example, Y. Zhou *et al*. (2020) alluded that lack of mutual trust between shippers and shipping

Table 2. Synthesis of drivers, barriers, and enablers of DT in maritime ports sector

	Degree rank	Drivers	Barriers	Enablers
High degree centrality	31	Regulatory compliance		
	31		Information sharing	
	31		Digital literacy	
	31		Investment cost	
	31			Stakeholders integration
	31			Ports readiness for change
	30			Digital platform
	29		Cybersecurity concerns	
	29		Digital awareness	
	29		Port governance structure	
	29		Environmental uncertainty	
	29			Collaboration
	29			Digital innovation
	29			Digital strategy
Medium degree centrality	28	Port process optimization		
	28		System interoperability	
	28		Ports culture	
	28			Trust
	27	Sustainability consciousness		
	27			Digital leadership
	26			Industry 4.0 technologies
	26			Top management support
	26			Digital champion

(*continued*)

Table 2. (*continued*)

	Degree rank	Drivers	Barriers	Enablers
Low degree centrality	24		Legacy systems	
	23		Lock-in effect	
	23			Change management
	23			Digital business model
	23			Digital maturity
	21		Agility	
	17		Asymmetric information	
	17			Co-opetition
	16		Diffusion of innovation	

Source: Authors' own elaboration from empirical literature review.

companies has precluded open information sharing on container capacity which perceivably eliminates bargaining power of the latter and therefore their competitiveness. Undoubtedly, poor information management in the port ecosystem is costly as it may lead up to 20% increase in ports operational budget (Gausdal *et al.*, 2018). However, nascent technologies like blockchain may secure information sharing among stakeholders (Bavassano *et al.*, 2020; Lin, 2023). Certainly, information sharing is one of the cornerstones to successful implementation of DT as it influences other aspects such as collaboration among stakeholders.

Digital Literacy. The knowledge repository of maritime ports' stakeholders has a bearing on the perceived usefulness of advanced digital technologies, which also influence their pace of acquisition and deployment. Digital literacy is the extent to which port stakeholders use their cognitive abilities to exploit the affordances of digital technologies as they create and capture value along maritime supply chains. Operational and technical skills are increasingly becoming essential assets amid the ubiquity of novel digital technologies (Chowdhury *et al.*, 2023). However, people may have strong cognitive abilities, but may lack the necessary knowledge about digital tools and their potential contribution in the actual context where they are supposed to be used. Consequently, maritime ports experience low digital literacy amongst stakeholders and internal human capital (González-Cancelas, Molina Serrano, *et al.*, 2020; Inkinen *et al.*, 2021). Some researchers have attributed this deficiency of skills to the lack of training to both employees and stakeholders, which consequently impair an understanding of digital affordances in business improvement (Baum-Talmor and Kitada, 2022; Raza *et al.*, 2023; Zhang and Lam, 2019). For instance, Gekara and Nguyen (2020) revealed that digital initiatives to install container terminal operating system (CTOS) at the Port of Mombasa failed

partly due to workforce's sabotage and limited technical knowhow on the users of the installed CTOS. The authors further argued that the workforce's limited knowledge and skills to operate the new system effectively instigated overdependence on the external system developer to resolve even the minor technical and operational glitches. They also reported that ports' workers often ignored using system devices such as hand-held terminals and vehicle mounted terminals because they found them difficult or unfamiliar (ibid). In contrast, ports stakeholders' digital literacy may stimulate adequate actions and investments during strategic decision-making process (Philipp, 2020) and harness appropriate cultural climate for digital innovation (Hsu *et al*., 2023; Lambrou *et al*., 2019).

Investment Cost. High investment and implementation costs have been cited as one of the most prominent roadblocks to implementing DT initiatives in maritime ports (Bavassano *et al*., 2020; Carlan *et al*., 2017; Gausdal *et al*., 2018; Inkinen *et al*., 2021; Nicoleta *et al*., 2020). While some authors contend that industry 4.0 digital technologies are inexpensive, this contention may contradict important aspects relating to the organizational transformation such as training requirements for system users, systems (re)configurations and architecture that enhance the efficacy of existing IT systems uninterruptedly (Zhang and Lam, 2019), port size (Poulis *et al*., 2020), and the extent of digital maturity of ports' IT repertoires (Heilig and Voß, 2017). Thus, hardware, software, and training costs may present significant barriers for ports with especially limited budget. For instance, Inkinen *et al*. (2019) revealed that all medium-sized ports in Finland lagged in digitalization endeavors. The authors attributed the slowness to the size of the ports and their close association with limited financial resources and constrained strategic choices. Likewise, unclear cost and benefit distribution among port stakeholders may considerably attenuate their cooperation in implementing DT initiatives (Carlan *et al*., 2017; Lin, 2023; Seo *et al*., 2023). For instance, Y. Zhou *et al*. (2020) investigated the barriers to blockchain implementation among Singaporean maritime organizations and revealed that capital expenditure on the blockchain project and requisite training and upskilling of employees constituted perceived high investment cost amongst the interviewed maritime professionals. The authors argued that investment in blockchain technology requires financial stability that the maritime industry may lack (ibid).

Cybersecurity Concerns. Latest digital solutions are arguably more secure (Hsu *et al*., 2023; Inkinen *et al*., 2021). However, interconnected devices on shared digital platforms increase the risk of costly malicious attacks and data breaches especially, when we consider the novelty and infancy of technologies such as blockchain (Lin, 2023; Yang, 2019). Increasingly, data and information have become sensitive strategic resources and aspects of operations warranting aggressive safeguarding (Gekara and Nguyen, 2018; Kuo *et al*., 2021; Nicoleta *et al*., 2020). Following this, stakeholders such as freight forwarders have expressed concerns about the confidentiality of their business data on a shared open platform for container booking processes (Zeng *et al*., 2020) in case it becomes preyed upon (Raza *et al*., 2023). Examples of malicious attacks are not uncommon in the maritime domain. For instance, the port of Antwerp in Belgium came under cyberattack when the perpetrators smuggled cocaine and heroin through legitimate cargos by hacking the port's IT systems (Chang *et al*., 2020). Meanwhile, the shipping giants Maersk, MSC, Hapag Lloyd, ONE, and CMA CGM came under cyberattacks in 2017 (Afenyo and

Caesar, 2023). While these companies had been thought to have airtight cybersecurity systems, such attacks set a bad precedence for sectors such as ports which may aspire to venture into new technologies for which they have limited knowledge about. Thus, the perception of vulnerabilities inherent in new digital solutions daunts ports' stakeholders from implementing them (Gómez Díaz *et al*., 2023; González-Cancelas, Molina, *et al*., 2020; González-Cancelas, Molina Serrano, *et al*., 2020). This fact exacerbates stakeholders' mistrust in advanced digital technologies' data management capabilities (Inkinen *et al*., 2021). Thus, perceived digital security risks increases reluctance of maritime ports to experiment with and exploit digital technological solutions, consequently making ports and maritime supply chains uncompetitive (Kashav *et al*., 2022).

Digital Awareness. Digital awareness represents ports' knowledge repository and inquisitiveness about the functioning and affordances of Industry 4.0 digital solutions. It is the extent to which maritime ports consciously recognize the potential of novel technological solutions and proactively engage in pursuit of their affordances. It may be rooted in the ports' experimental culture and quest to invoke new business models to stay competitive (Chowdhury *et al*., 2023; Gómez Díaz *et al*., 2023). In fact, ports' lack of digital awareness has been attributed to their staggering DT initiatives (Philipp, 2020). Yet, lack of knowledge and awareness of how digital technologies may affect maritime ports' businesses has been linked with their slow rate of acquisition (Lin, 2023). A few exceptions include container terminals such as Victoria International Container Terminal (VICT) in Melbourne Australia, Container Terminal Altenwerder (CTA) in Hamburg, Germany, Euromax Container Terminal in Rotterdam, Netherlands, and Norfolk International terminals in Virginia (Gekara and Nguyen, 2018) which are fully automated with modern digital technologies and are commonly regarded as the industry's best practice role models. Indeed, top executives' digital awareness is an essential internal dynamic capability that underscores the capacity to sense and shape opportunities and threats by reconfiguring intangible and tangible ports assets (Raza *et al*., 2023).

Port Governance Structure. The influence of port governance models on DT trajectories are discernible through their influence on organizational structure (Lambrou *et al*., 2019; Zhang and Lam, 2019), technological integration (Inkinen *et al*., 2021), and decision-making processes (Zeng *et al*., 2020). This barrier varies greatly on a continuum between publicly owned and hybrid port models with private and public entities collaborating in the ownership and management of port operations (Philipp, 2020). Public port authorities encounter challenges due to bureaucratic decision-making processes and limited agility (Zeng *et al*., 2020), hindering the rapid adoption of digital innovations (He *et al*., 2023). However, their stability and long-term vision enable strategic planning for sustainable technology integration. On the other hand, private port operators driven by profitability and operational efficiency exhibit greater responsiveness to DT, investing readily in digital solutions to optimize processes and improve customer experience. The landlord port model, by segregating infrastructure ownership from operations, fosters DT through competition among terminal operators and the pursuit of cutting-edge technologies. Nevertheless, hybrid port governance models – combining elements of public and private sector involvement (He *et al*., 2023; Inkinen *et al*., 2021), offer both strategic planning and entrepreneurial spirit but may face complexities in decision-making. For instance, (Zeng *et al*., 2020) found out that government power and organization ownership structure

impacted the adoption of inter-organizational information systems in the maritime supply chain and that, actors must recognize disparities among various ownership structures.

Environmental Uncertainty. In this context, environmental uncertainty refers to an external outcome that may jeopardize the efficacy of ports' or its stakeholders' DT endeavors. Generally, environmental uncertainty should be a driving force that propels ports to acquire new digital solutions to mitigate risks (Kuo *et al*., 2021). Oxymoronically, it acts as a barrier to effective implementation of DT in ports. Firstly, as myriads of policies, regulations, and trade agreements change constantly, they make it difficult for ports to know what digital tools and solutions will work in the future (Inkinen *et al*., 2021; Raza et al., 2023; Y. Zhou et al., 2020). As ports are entwined in global economy and geopolitical events, their services increasingly fluctuate with these dynamics making it hard for them to determine return on investments of novel digital solutions (Gómez Díaz et al., 2023; Lin, 2023). For instance, the ongoing trade tensions between China and the US, and the Russian invasion of Ukraine impact both ports' businesses as well as those of stakeholders such as shipping lines and freight forwarders in terms of higher freight fees, longer transit times, and port congestion. Secondly, an unprecedented exponential growth in Industry 4.0 technologies presents uncertainty to ports regarding which digital solutions to adapt and how to implement them effectively as well as unified standards for data transmission, sharing, an interoperability (Lin, 2023). Meanwhile, embarking on novel technologies adds another layer of uncertainty regarding displacement of jobs and emergence of new skills requirements which can instigate resistance to change as digital talents are reportedly scarce and do not match the pace of DT (Gekara and Nguyen, 2018, 2020; Raza et al., 2023). Irrespective of the digital solutions that ports adopt, the existence of stable national broadband connectivity has been brought into the spotlight. For instance, the flickering internet connectivity (provided by another governmental agency) was reported to force the Port *of* Mombasa's workforce and its wider array of stakeholders to switch between digital and manual systems thereby suppressing the port's effort to automate its container terminal (Gekara and Nguyen, 2020). Furthermore, while blockchain for instance, can provide an opportunity for ports to streamline efficiency and enhance stakeholders experience, it also introduces a layer of uncertainty regarding interoperability, scalability, and potential disruptions to existing ports operations.

Enablers. These are factors that facilitate the attainment of successful DT in ports sectors. We identified 15 enablers of which we resorted to discussing only 6 of them based on their degrees of centrality.

Stakeholders' Integration. This refers to synchronization of port stakeholders' information and workflows and the way their disparate systems communicate with each other. The ports sector has a plethora of technologies relating to ports' operations, i.e., port community systems (PCS), single window systems (SWS), electronic data interchange (EDI), radio frequency identification, among others (Bauk *et al*., 2017; Peynirci, 2021). These conventional technologies have been used by port authorities for years to integrate ports' actors. While they may lack scalability, retrofitability, and interoperability, they foster the adoption of advanced technologies such as digital twins, artificial intelligence, block chain, and internet of things (Hsu *et al*., 2023; Lin, 2023; Raza *et al*., 2023) as

supporting baseline technologies. Considering the value creation logic that lies in stakeholders such as customs authorities, shipping lines, freight forwarders and the ports themselves, initiatives to integrate their interfaces may further strengthen value creation and capture of the ecosystem, engendering ports' competitiveness, and consequently bolstering inclination to embark on novel digital technologies (Carlan *et al*., 2017; Hsu *et al*., 2023; Seo *et al*., 2023). Arguably, the more integrated the stakeholders are, the more likely they are to implement DT initiatives that further benefit them.

Ports and Stakeholders Readiness for Change. We define this as the extent to which maritime ports embrace changes and readily undergo digital metamorphism. The exploitation of novel and cutting-edge digital technologies lies in the complex interplay of management measures and employees' knowledge and skills, as well as functional information technology processes (Philipp, 2020). These elements increasingly require concerted efforts of maritime ports to embrace digital transformative changes. In fact, Philipp (2020) and González-Cancelas, Molina Serrano, *et al*. (2020) suggest that neither innovative digital technologies alone nor human aspects are a panacea to successful DT of maritime ports. They argue that successful implementation of DT in ports relies on such aspects as alignment of existing culture, structure, personnel, and tasks (Gómez Díaz *et al*., 2023; González-Cancelas, Molina Serrano, *et al*., 2020; Iman *et al*., 2022) for all stakeholders involved. Yet, an empirical study by Bavassano *et al*. (2020) revealed a heterogeneity in implementing digital initiatives such as blockchain, among maritime stakeholders (i.e., shipping companies, port authorities, regulators) and attributed it to organizational and perceived market readiness aspects. The findings in this study underscore ports' attitudinal role towards change and the timeline upon which the change will materialize. For instance, some of the interviewed actors expressed concerns that it would take about 10 years for a blockchain initiative to materialize. Such a view exacerbates disinclination to invest in novel technologies (Bavassano *et al*., 2020).

Digital Platform. This concept entails a collaborative electronic platform that pulls ports ecosystems' stakeholders together, thereby enabling a smooth information sharing as it pertains to freight movements, vessel arrival times, port call processes, as well as interactions with hinterland actors (Carlan *et al*., 2017; Lambrou *et al*., 2019). The implementations of digital platforms such as PortNet (Fedi *et al*., 2019; Inkinen *et al*., 2019), and blockchain technology (Bavassano *et al*., 2020; Lin, 2023; Philipp *et al*., 2019) have permitted the rationalization of port processes and bolstered coordination between ports and their stakeholders. In fact, digital platforms such as port community (PCS) systems and national single window systems (NSWS) are a precursor for more digitalized ports as they create paperless ports and streamline administrative procedures (Bisogno, 2015; Carlan *et al*., 2017; Hsu *et al*., 2023; Seo *et al*., 2023). However, the development of common digital platforms among a diverse set of stakeholders is arguably a daunting task (Gekara and Nguyen, 2020; Inkinen *et al*., 2019) because benefits and cost of such initiatives may not equally accrue and resonate with all stakeholders involved, unless powerful digital orchestrators emerge to spearhead the process. For instance, the Port of Rotterdam's vision 2030, has had long term strategic vision that incorporates stakeholders' opinions thereby obtaining their buy-in in initiatives that impact the port's ecosystem.

Collaboration. This is an extent to which maritime ports stakeholders synchronously pool resources (tangible and intangible) in implementing DT initiatives. Unequivocally, successful implementation of DT initiatives depends on well-coordinated efforts of most ports' stakeholders (Camarero Orive *et al*., 2020; Raza *et al*., 2023). Stakeholders' collaboration stems from shared innovation vision, commitment to open communication, mutual respect, and willingness to work together, lack of which exacerbates fragmented transformational initiatives (Carlan *et al*., 2017; Kuo *et al*., 2021; Lin, 2023). In this vein, Gekara and Nguyen (2020) found that container terminal automation initiative failed due to lack of collaboration from internal workforce and freight forwarders who were external users when they bypassed the installed system and maintained manual transaction of freight clearing documentations. Additionally, the self-organizing interplay of disparate actors, requires formal agreements for developing and implementing collaborative solutions (Inkinen *et al*., 2021; Vairetti *et al*., 2019), as well as commitment and willingness of experienced stakeholder partners with whom to spearhead the implementation of DT (Y. Zhou *et al*., 2020). For instance, to achieve mutual trust and communication ports' stakeholders must collaborate in effectuating the enablements in blockchain technology (Gómez Díaz *et al*., 2023; Lin, 2023; Raza *et al*., 2023). To elaborate this, the Port of Antwerp collaborated with T-Mining, a blockchain solution provider on a digital project to secure the flow of documents through smart contracts which has enabled it to share real-time secured documents and related information with all interested parties (Chang *et al*., 2020; Zhao *et al*., 2023). Examples of the efficacy of collaboration can also be drawn from shipping sector where IBM created a blockchain digital solution, TradeLens in collaboration with Maersk a global shipping leader (Bavassano *et al*., 2020). This solution has enabled real-time tracking and planning of shipping containers and the automation of shipping documents flows including letters of credit, commercial invoices, certifications, and bill of lading which are typically prone to fraud (Chang *et al*., 2020). The TradeLens platform serves stakeholders such as port authorities, public authorities and freight forwarders and other shipping companies such as MSC, and CMA CGMA (González-Cancelas, Molina, *et al*., 2020). However, due to disparities in resources and perceived benefits of adopting inter-organizational digital systems, port stakeholders will likely experience protracted and complicated negotiation process (Vairetti *et al*., 2019).

Digital Innovation. A digital innovation captures the extent to which ports explore new ways of delivering superior products or services and differentiated stakeholders value by exploiting novel digital technologies. In fact, the outcome of a digital innovation is noted in its impact on processes (i.e., streamlining the efficacy of port processes) (Carlan *et al*., 2017; Gausdal *et al*., 2018), value creation and capture model (i.e., new digital business model) (Gausdal *et al*., 2018), and engagement model (i.e., stakeholders experience) (Bavassano *et al*., 2020; Philipp, 2020). Nevertheless, ports exploit digital innovation in aspects they deem the former fits best with strategic business needs (Gausdal *et al*., 2018). For instance, the port of Antwerp, through its ambition to become a European leader in IoT has embarked on digital initiatives such as blockchain solution which has enabled it to automate end-to-end physical flow of containers, automate document flows, and integrate data silos (Chang *et al*., 2020). Digital innovations such as track and trace, automatic identification systems (AIS), blockchain, electronic data interchange

(EDI), among others, have the potential of facilitating imperative ports' continuous DT (Bavassano *et al*., 2020; Carlan *et al*., 2017; Inkinen *et al*., 2019; Lin, 2023).

Digital Strategy. ICT deployment strategies have a direct bearing on the extent to which maritime ports acquire and experiment with digital technological solutions. A digital strategy is the one that uses ICT infrastructure (both soft and hard) as a core of ports' business strategy reconfiguration. It deploys digital innovation and integrates it with core port processes thereby enabling them to create and capture superior value among its participating stakeholders (Lambrou *et al*., 2019; Raza *et al*., 2023). A particular digital strategy has a bearing on the outcome of DT initiatives. For instance, pathfinder ports (i.e., Rotterdam, Antwerp, Singapore, and Hamburg, among others) experiment with latest technological breakthroughs and take risks, thereby, influencing positively DT outcomes such as full port integration with all stakeholders of the industry (Bauk *et al*., 2017; Hsu *et al*., 2023; Kapidani *et al*., 2020; Philipp, 2020; Raza *et al*., 2023). On the contrary, late adopters or laggards, where majority of ports falls, have missing digital strategy and only adopt new technology necessary to safeguard their business operations (Bauk *et al*., 2017; Inkinen *et al*., 2019; Y. Zhou *et al*., 2020). Between the two extremes are monitor ports, early majority (or adopter ports), and developer ports (Bauk *et al*., 2017; Philipp, 2020). Effective digital strategy may enable ports to persevere transformational endeavors in the face of unprecedented failures. For example, Inkinen *et al*. (2019), in their empirical research on DT trajectories in Finish ports revealed that majority of the respondents affirmed to have adopted an observer's role as opposed to taking the leading role which has resulted to low digitalization outcomes among Finish ports. Besides, the authors revealed that Finish ports' DT evolves as a part of strategic choice which they openly argued was missing. The authors identified that, of the interviewed Finish ports, none had a designated person for digital service development (ibid).

To sum up, Fig. 4 presents an aggregated framework that conceptualizes the drivers, barriers, and enablers of DT in the maritime ports sector. As the framework shows, despite the pressure from competition, regulatory authorities, and sustainability consciousness, achieving DT is not straight forward. There are several barriers that can hinder that journey. However, several factors serve as enablers of DT implementation.

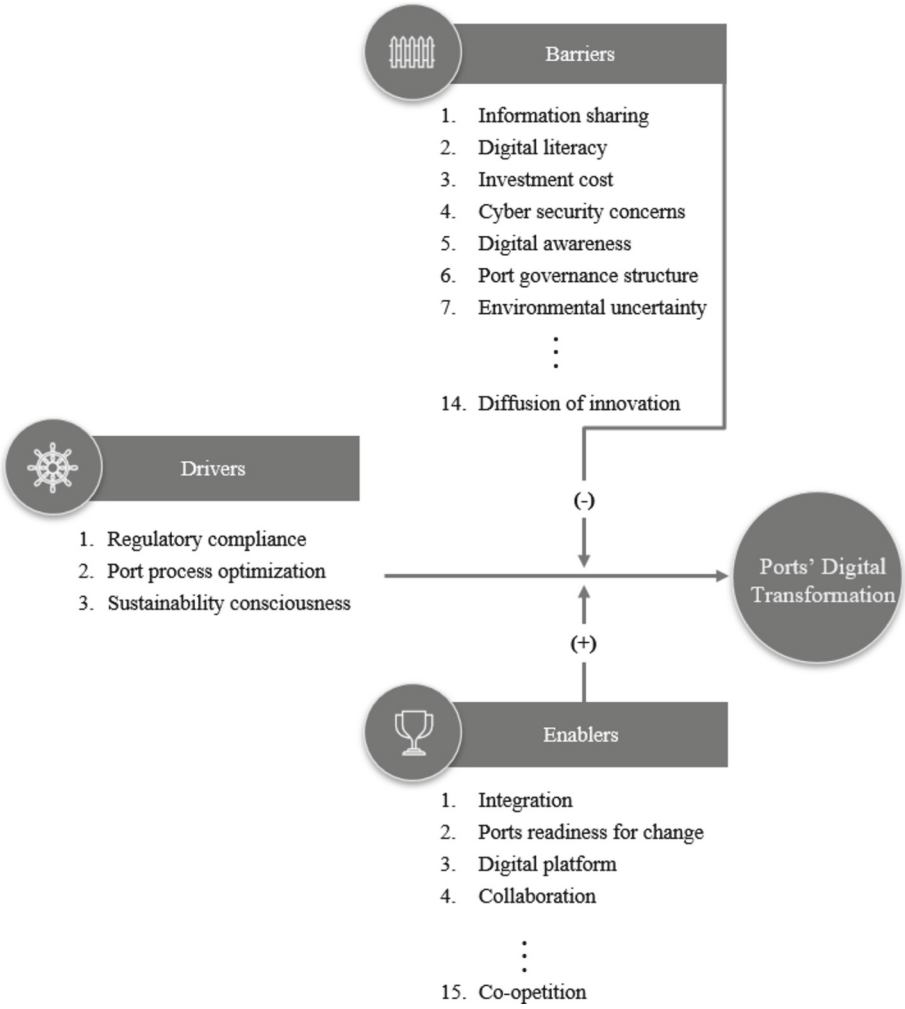

Fig. 4. Framework of drivers, barriers, and enablers of DT in the maritime ports. Source: Authors' own elaboration based on empirical literature.

3.2 DT Idiosyncrasies and Dimensions

DT in maritime ports refers to the process that results in a fundamental transition in the way ports operate, create, and expropriate value. Undeniably, DT of maritime ports is oxymoronic as it presents both opportunities and significant disruptions. Ports may leverage the affordances of advanced digital technologies to improve efficiency, safety, and sustainability. Contrarily, to leverage such affordances ports must conscientiously integrate novel technologies into their existing processes, infrastructure, and legacy systems while balancing the complexity of operations which involve numerous stakeholders (Chowdhury *et al.*, 2023). Moreover, coordinating and integrating disparate stakeholders' systems and processes may be a potentially daunting task.

Perhaps, the peculiarity of DT resides in its pervasive effects across several ports operational and structural aspects such as ports business process, business model, structure, people, products and services, and engagement model (Chowdhury *et al.*, 2023; Raza *et al.*, 2023). These dimensions (see Fig. 5) are intertwined and require holistic ports internalizations that go beyond mere technological acquisition and implementation. Undoubtedly, advanced digital technologies transform processes and enable ports to reconfigure strategically value creation logic sustainably. Achieving this outcome requires changing the decision-making processes, ports' way of doing things, and workforce's skillsets. These organizational aspects have received considerable fragmented attention in extant port literature (González-Cancelas, Molina Serrano, *et al.*, 2020; Inkinen *et al.*, 2021; Kapidani *et al.*, 2020; Y. Zhou *et al.*, 2020).

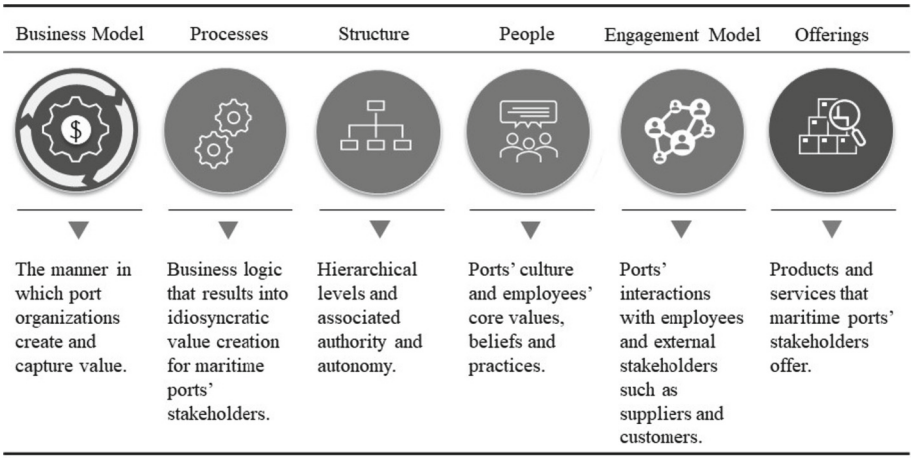

Fig. 5. Dimensions of DT. Source: Authors' own elaboration**.**

Ports' Business Model Dimension. A business model entails a strategic blueprint of how ports create value proposition. With DT, ports transition into digital business models from traditional business models (i.e., using digital platforms that optimize port's interactions with its external stakeholders). This adoption of business model enables ports to generate new value proposition and revenue streams (Kuo *et al.*, 2021; Sanchez-Gonzalez *et al.*, 2019; Seo *et al.*, 2023). Given the complexity of port processes and multiplicity of actors, ports need to develop a digital supply chain as a new business model in collaboration with shipping lines, governmental agencies, freight forwarders, customs authorities, among others. For instance, Chowdhury *et al.* (2023) and Seo *et al.* (2023) report that the port of Singapore introduced a digital platform, digitalport@SGTM which optimizes vessel, health, and immigration clearances. Meanwhile, the ports of Hamburg, Antwerp, and Rotterdam have implemented smartPORT, NxtPort, and PortXchange business models respectively, which streamline port operations such as real-time cargo tracking, customs clearance, berth availability, and vessel schedules (Gausdal *et al.*, 2018; Hsu *et al.*, 2023; Inkinen *et al.*, 2021). With digital technologies such as internet of things (IoT), sensors, and big data analytics, these ports can take strategic decisions that are grounded

in real-time data thereby significantly minimizing port congestion and waiting times. Furthermore, the platforms streamline connectivity and transparent interactivity of all actors in a systematized way hence, engendering ecosystems competitiveness at large (Hsu *et al*., 2023). We contend that the DT needs of ports vary depending on their business models, which can be influenced by factors such as the complexity and volume of cargo they handle and their heterogeneity. For example, a large container port like Rotterdam in the Netherlands, may require advanced technologies such as automation and artificial intelligence to optimize cargo handling and reduce turnaround times. In contrast, a smaller port like Bremanger in Norway that handles bulk cargo may require simpler DT solutions such as digital documentation and real-time tracking of cargo.

Ports' Process(es) Dimension. It is a logical order of interrelated activities that ports, and its stakeholders perform to receive and discharge cargo to consignees. It relates to how ports bring value proposition to life and harness economic rent. DT has certainly had a significant bearing on the port processes. For instance, the introduction of digital technologies has facilitated greater automation of port processes, such as cargo handling, terminal management, and vessel scheduling. Automation such as digital twin has allowed the port of Hamburg to increase transparency of process management and reduce the degree of human interventions in the operations of port processes (Camarero Orive *et al*., 2020; Chowdhury *et al*., 2023). As port processes are inextricably intertwined in the actions of many stakeholders, DT has enabled ports to better integrate their operations with those of their stakeholders, such as customs authorities, shipping lines, freight forwarders, and railway and trucking companies. Such integration has engendered substantial coordination and collaboration amongst these value chain actors which have further enhanced efficiency and reduced delays in some pioneering ports such as Antwerp, Gothenburg, Qingdao, Rotterdam, etc. (Lin, 2023; Raza *et al*., 2023). Furthermore, the use of big data analytics enables ports to rationalize data captured by IoT and sensor devices to predict vessel arrival times, optimize assets utilization in cargo handling operations and improve productivity. However, stakeholders express mixed feelings about the pros and cons of digital technologies. For instance, Gausdal *et al*. (2018) in their empirical work on Norwegian maritime industry found that blockchain technology did not provide the right fit for the whole shipping industry. The authors contended that nuanced attention must be paid to specific actors' requirements in terms of size, goals, vision, financial capacity, and interest in a particular innovation (ibid). Therefore, the journey to digital maturity is long and winding as ports are said to be at different stages of implementation of DT initiatives (Inkinen *et al*., 2021; Philipp, 2020). At one extreme, there are ports that are digitizing documentation flow internally and across relevant stakeholders (i.e., the port of Dar es Salaam in Tanzania), at the other extreme, there are ports that have automated all their processes including integration with relevant stakeholders (i.e., Gothenburg port in Sweden).

Ports' Organizational Structure Dimension. DT allows ports to redefine hierarchical and functional structures due to increasing need for faster decision-making, process transparency, and open communication lines (Seo *et al*., 2023). The increasing use of digital platforms such as port community systems and electronic single windows (Peynirci, 2021) shifts structural power across stakeholders, however, affords ports greater vertical and horizontal collaborations and flexibility in value creation and capture (Philipp,

2020). For instance, the use of blockchain's smart contracts secures ports stakeholders' transactions when only relevant actors can verifiably effectuate their value creation equation. The level of transparency goes a long way to enforcing greater accountability meanwhile streamlining ports' operations. Moreover, open platforms such as those for container bookings have impacted the decision-making tactics of actors such as freight forwarders, shippers, and shipping lines, where they previously had to work with limited asymmetrical information (Zeng *et al*., 2020) which arguably had been used as a source of bargaining power and competitiveness. The authors further revealed that freight forwarders expressed concerns that valuable customer information such as prices could be accessed and taken advantage of by the Onetouch (open platform) system's provider, hence their reluctance to use such system (Zeng *et al*., 2020). Thus, storing data on the cloud and introducing other organizations in the value creation of freight forwarders seemed to infiltrate their sphere of influence. It follows that hierarchical organizational structure instigates bureaucracy that contradicts the need for agility and greater decentralized autonomy in decision-making. More horizontal structure will allow ports to establish cross-functional team structure that fosters collaboration by integrating both business and digital teams into a high-performing team. Furthermore, ports may have to restructure to accommodate the emergence of new roles which specialize in data analytics, automation, and artificial intelligence (Raza *et al*., 2023; Zhang and Lam, 2019). As Kuo *et al*. (2021) stresses, organizational structure is pertinent building block of DT and therefore it is affected by it.

Ports' People Dimension. The ports' workforce are the ultimate users of any digital system as such, they directly impact their success of failure. DT, due to its evolutionary and combinatorial natures, may pejoratively instill fear of change and intensify negative attitudinal prejudices towards acceptance and use of digital solutions. In fact, this tendency may be more pronounced among maritime ports with low technological diffusion (Djoumessi *et al*., 2019; Zeng *et al*., 2020). Consequently, stalling efforts to implement digital initiatives at port level and across ports' stakeholders. Nonetheless, implementation of DT necessitates ports' workforce reskilling and upskilling because of changes in work cultures and practices (Gekara and Nguyen, 2018; Inkinen *et al*., 2021; Y. Zhou *et al*., 2020). For instance, of the very few remaining workforces in Australian ports require more analytical skills than physical skills as they need to adeptly interact with digital systems' diagnostics and intervention (Gekara and Nguyen, 2018). Furthermore, Gekara and Nguyen (2020) revealed that the failure of a digital initiative to automate Mombasa container terminal was partly due to limited steady training and skilling effort to the existing and new recruits after the digital project had been rolled out. Therefore, digital skills management and literacy are requisite conditions that may support ports' continuous adaptation through DT (Gekara and Nguyen, 2018).

Ports' Engagement Model Dimension. Engagement model entails a point of contact between the ports and its broad array of users. DT impacts how ports interact internally and externally with customers and other stakeholders (Kuo *et al*., 2021). With DT, technologies such as big data, analytics, and IoT may allow ports to transition into digital channels or combine both physical and digital channels using social media and other e-commerce platforms. For instance, the use of big data may allow ports to garner and analyze large amounts of data about their operations such as ship arrivals and departures,

cargo volumes, and whether conditions. This data can be used to optimize port operations such as scheduling cargo arrivals and departures and predicting and mitigating potential delays or disruptions. Likewise, analytics can afford ports a capability to synthesize vast amounts of data they generate thus gaining insights that permit data-driven decisions whereas, IoT can allow remote control of connected ports' devices such as cranes, trucks, and containers (Gekara and Nguyen, 2018). While social media platforms will enable ports to inform customers about cargo arrivals and departures, e-commerce can facilitate online transactions where port users can book cargo shipments, track their shipments, and make payments. This will enable ports to harness intelligent information real-time and thus take effective decisions to effect positive outcomes such as vessel arrival scheduling, and trucking appointments. Likewise, port users may garner information relating to the status of their shipments, pay port dues online, and communicate with port authorities in real-time. This dimension is closely interlinked with the automation of ports' business processes. The key is to collect intelligent information and disseminate it to appropriate stakeholders. For instance, the use of a single point of entrance of cargo manifest may save ports, clearing and forwarding companies, customs, and other public authorities, time and duplication of efforts.

Ports' Offerings Dimension. DT affects value added logistics that ports and its stakeholders provide to final consignees. Thus, ports can leverage digital technologies and harness more value in their service offerings. For instance, ports can use straddle carriers with integrated electronic data interchange (EDI) or IoT sensors to streamline identification, tracking and tracing of cargo movements both ship-to-shore and in the yards (Camarero Orive *et al*., 2020; Carlan *et al*., 2017). Moreover, the use of temperature-controlled warehouses may attract more cold-chain (i.e., perishable food and drink market). Meanwhile, artificial intelligence (AI) and sensor technologies may reduce energy consumption, thereby, enabling ports to sustainably cut cost and lessen environmental footprint (Raza *et al*., 2023). Robotic technology may reinforce value added activities such as weighing, repalletizing and wrapping, packaging and consolidation for onwards distribution. Technologies that allow ships to recharge electricity while on port call enable ports to reduce greenhouse gas footprint. Tracking and tracing technologies will allow ports to accurately share port traffic information with stakeholders such as trains, truckers, shipping lines, among others.

We posit that the preceding six dimensions underlie differing transformational trajectories within ports and across stakeholders. While there as some ports that have traversed and transformed in all dimensions (i.e., smart ports as Hamburg, Rotterdam, and Victoria International Container Terminal) (Kuo *et al*., 2021; Philipp, 2020), majority seem to chart sketchy paths which presumably underscore the many interacting factors as illustrated in Fig. 4.

4 Managerial and Policy Implications

4.1 One Size Does Not Fit All

We concur that DT as a tool does not fit all ports equally. It requires a nuanced analysis of its affordances and a more pragmatic understanding of its applicability in different contexts and conditions. While there has been an increasing need to improve efficiency

and productivity in the maritime industry as a whole and ports in particular using novel digital technologies, we argue that not all ports may be suitable candidates for DT. One plausible explanation is that the capital expenditure involved in procuring new equipment and digital infrastructure (i.e., hardware and software) may extend to millions or even billions of dollars, far out of reach of many ports. Yet, ports that handle specialized cargo such as containerized, hazardous, perishable, or liquid bulk may require more significant investments in DT due to the need for specialized equipment, storage, and technology. For instance, implementing DT solutions in ports that handle high-value cargo such as chemicals as is the case with the Port of Antwerp in Belgium, may require significant investments in security, tracking, and monitoring, systems than ports that transit low-value cargo such as timber in the port of Riga in Latvia. Moreover, ports that handle less specialized cargo such as grain bulk may require less investment in DT and therefore investment cost in that respect may not be of concern. Again, the investment costs emanating from DT may not be a huge barrier for ports that handle large volumes of cargo than for ports which handle limited volumes of cargo because large economic rents that accrue from massive volumes may justify investments in DT that optimize operations. Thus, cosmetic improvements on manually operated systems – through digitization might be a more pragmatic approach for ports with limited cargo traffic to warrant significant investments in digital innovations. In fact, some ports may make-do with digitization of paper documentations, data, record keeping and other administrative and documentation formalities. Therefore, as the needs of different ports evolve, a transition towards more advanced DT may make more sense. With the findings in this study, we are convinced to have unfolded peculiarities of DT and provided anecdotal evidence and insights from meaningful cases in the port industry. Furthermore, we provide a caveat that the thematic drivers, enablers, and barriers of DT in maritime ports may play out differently across a range of ports around the world. For instance, the issue of internet connectivity is a much relevant environmental uncertainty aspect in contexts where ports experience weak and unstable connectivity because of over-reliance on governmental internet service providers who often may lack ambition to develop stronger networks and bandwidths (Gekara and Nguyen, 2020). In this vein, most emerging economies are currently transitioning into 3G and 4G internet technologies while their developed counterparts are charting 5G which provides low latency and much faster data transmissions. The latter supports interconnected devices such as automated guided vehicles, automated rubber-tired gantry cranes, remotely controlled ship-to-shore cranes, and analytics of large amounts of data generated by these devices (González-Cancelas, Molina, *et al.*, 2020; Inkinen *et al.*, 2021). Nevertheless, the need for internet connectivity is a must for all ports, large or small, as there are standard shipping documentations that must be shared with relevant stakeholders to rapidly clear cargos through ports. Several other caveats are discussed here under:

Regulatory compliance is a universal driver of DT, however, may be greeted with different action points. For instance, ports that exist in geographical locations such as Europe and America where there is a greater requirement for energy transition from fossil fuels to renewable energy may fast track DT initiatives as the means to comply to strict regulations and accommodate modern ships design and size. In this regard, ports in these locations may implement DT initiatives such as digital twin, IoT, A/VR,

and AI to streamline port operations by reducing movements and congestions of ships and trucks which are prime candidates for CO2 emissions. On the other hand, ports in Africa may be subjected to slightly lax regulations where emphasis may be placed on digitizing documentation flows and automating selected aspects such as containers offloading, stacking, and delivery.

4.2 Stakeholders' Alignment Challenges in Ports DT

Throughout this paper, we have alluded to the importance of stakeholders' involvement in DT's success or failure. Examples such as those offered by Gekara and Nguyen (2020) on the failure of TOS initiative due to misalignment of goals across both internal port's personnel and external port users – the freight forwarders; and Heilig *et al.* (2017) on the failure of the port of Hamburg to get stakeholders to use smartPORT digital platform back in 2017, stress the importance of stakeholders' considerations. Moreover, ports such as Long beach and Los Angeles have continued to enter renegotiations with International longshore and warehouse union (ILWU) due to possible ramifications of introducing novel technological solutions on the existing workforce. These anecdotes illustrate the fact that digital technologies as tools are as good as the strength of the alignment of all port actors who may directly be impacted by such digital initiatives. In contrast, ports like Rotterdam, Antwerp, and Gothenburg have managed to develop programs that are inclusive in terms of integrating views of different stakeholders including developing collaborative solutions together. This consequently impacts the sense of ownership among stakeholders and entice their buy-in. Therefore, port authorities must look up to initiatives that involve major stakeholders such as workers associations, government agencies, shipping lines, and freight forwarders as an immediate solution to minimize the risk of system failure due to less optimal critical mass. They may also involve these stakeholders in identifying opportunities for collaboration and innovation.

4.3 Embracing Ports' Digital Ecosystem as a New Imperative Normal

Although DT endeavors are pervasive, they are idiosyncratic to different ports' stakeholders. For instance, ports can serve as central hubs for the development of digital technologies and infrastructure, establishing partnerships with other stakeholders to share data and knowledge to foster innovation and improve efficiency. Meanwhile, support from the shipping community may leapfrog digitalization projects in maritime ports because the former has made significant strides in implementing DT initiatives (Poulis *et al.*, 2020). Moreover, the involvement of professional consulting firms in the project management and training of workforce may lessen the pain points in implementing DT initiatives. It is arguably beneficial to adopt digital technologies with ecosystem's enablement, however, ports and its stakeholders (i.e., government agencies, shipping lines, logistics providers, etc.) must be ready and willing to share information which can be made possible through application programming interface (APIs). This will enable ports to enhance their operational efficiency and minimize delays in cargo handling. Moreover, attribution of value to such investment among disparate port stakeholders remains an unsolved puzzle (Bavassano *et al.*, 2020). Information asymmetry that some actors such as freight forwarders live off may stimulate increasing resistance to adopting

an open platform by these critical stakeholders (Iman *et al*., 2022; J. Liu *et al*., 2021; Seo *et al*., 2023; Zeng *et al*., 2020). Importantly, government and regulators can significantly influence digitalization process by enacting friendly regulations and providing concessions and subsidies. For instance, governments can provide exemptions or tax incentives for ports and companies that invest in digital technology. A typical example is the port of Rotterdam in the Netherlands whose government had been instrumental in providing subsidies and incentives for the adoption of digital technologies. As a result, the Port of Rotterdam has become one of the most advanced and efficient ports in the world, with real-time tracking of vessels and cargo, automated cargo handling, and optimized cargo logistics. Meanwhile, workers associations can provide valuable insights into the needs and concerns of workers who are critical to port operations. They can participate in the development of training programs that help workers adapt to new digital technologies and ensure their rights and interests are protected.

4.4 Port-Wide Digital Leadership and Digital Talent Management

DT dictates unique skillsets that top executives need to steer transformational initiatives in the right direction. Likewise, digital knowledge is essential in talent acquisition, grooming, retention, and management of digital resources. Roles such as chief information/digital officers (CIO & CDO) are exceedingly trending as top requirements for a successful DT and go hand in hand with supportive lower-level structures of port organizations. Moreover, an employee-centric approach may stimulate employees' innovation and participation in the implementation of DT initiatives. Thus, primary users of digital technologies become the center stage of grooming and digital knowledge acquisition. Considering their position, ports' digital leaders should reasonably treat digital assets as core strategic resources and instill a digital mindset across the board. For instance, they may encourage collaboration among stakeholders such as shipping lines and customs authorities to share best practice and insights. They may also facilitate the adoption of digital solutions and platforms that enable secure and efficient information sharing among disparate stakeholders. Similarly, ports may establish innovation labs or incubators that can help them test and experiment with new technologies before deploying them on a large scale. Talent management may ensure that digitally adept workforce will be available to manage cybersecurity risks and respond with efficacy to any unprecedented malicious attacks such as hacking and cybervandalism. These steps will reduce the intensity of cybersecurity concerns as one of the major barriers that empirical literature asserts to cripple down DT initiatives among ports.

Furthermore, to overcome digital awareness challenge among port stakeholders, ports' digital leaders may strategize and acquire digital solutions that align with both internal and external stakeholders' requirements, meanwhile devising specific trainings to upskill and reskill personnel to ensure they can adeptly use adopted digital tools. Yet, to overcome environmental uncertainty barrier towards the adoption of DT, ports digital leaders can spearhead the culture of innovation and experimentation. This will afford ports agility in adapting to changing circumstances (i.e., continual emergencies of new technologies). Meanwhile, digital talent management will ensure that employees are equipped with the necessary skills and expertise to navigate uncertainty and respond effectively to new changes.

4.5 How Ports Can Sustain DT Endeavors

We argue that DT of ports is not an end in itself, that after having transformed all aspects of the port business ports can complacently relax. Instead, ports must espouse DT as a necessary facilitating mechanism to strategic reconfiguration and rejuvenation of their efficacy in ever-changing environmental dynamics such as the mounting need for data and physical infrastructure security, operational safety, process and procedural transparency, and sustainability. In fact, economics of transformation endeavors may be such that, ports may experience high investment and implementation costs in initial implementation initiatives. However, such costs may decline in subsequent transformations due to infused readiness for change and cumulative effect of previously acquired digital infrastructure (Carlan *et al*., 2017). Furthermore, the role of ports' digital leaders should stretch across IT departments and complement the overall strategic vision of ports. The latter calls for a unified view of both port business and IT strategies and the convergence of C-suite managers' interests towards advancing ports objectives holistically and collaboratively. Arguably, no matter how good novel digital solutions are, if ports' workforce cannot support and use them effectively, the true benefits of DT can hardly ever be achieved.

As DT pervades all spheres of ports aspects such as structure, workforce culture, processes, and port services, ports top executives' and executors' change management skills become an ever-requisite talent. Nevertheless, to overcome eminent resistance to change by the workforce, transformation initiatives may be introduced phase-wise. In the meantime, giving the workforce an opportunity to rethink their roles, grow into them, and take necessary steps to equip themselves in case of subsequent transformational endeavors.

5 Conclusions and Directions for Further Research

In this paper, we have developed a framework based on empirical evidence from the maritime ports sector. We have delineated drivers, barriers, and enablers antecedents to successful implementation of DT in ports and demonstrated how each antecedent impacts materialization of digitalization initiatives. We have also cautioned that our framework of drivers, enablers, and barriers of DT in ports is contingent upon such factors as port size, complexity, nature of cargo handled, geographical location of ports, and heterogeneity. We have argued that the barriers may be accentuated or minimized on a continuum of these elements. Similarly, drivers can have different stresses across different ports. Therefore, our analysis adds a layer of granularity that helps practitioners and academic community understand the peculiarities of DT endeavors. While this study has only developed a framework of drivers, enablers, and barriers of DT, its strength lies in the exclusive analysis of peer-reviewed, empirical literature. Its benefits are twofold: firstly, it addresses the shortfall of (Tijan *et al*., 2021) whose literature review included articled beyond the scope of maritime ports as explained elsewhere in this paper. Secondly, derivation of empirically generated factors forms a firm basis for the development of rigorous conceptual frameworks and hypothesis testing. Therefore, the foundation provided in this paper will incite the scientific community's quest to advance knowledge by testing associations and causal relationships among the factors this paper

has deemed critical. A generalization of the results will help augment our understanding of the realities of DT in the maritime ports and complement existing fragmented anecdotal accounts.

Further studies may examine how value co-creation influences maritime ports' synchronized implementation of DT initiatives. Furthermore, future research on cybersecurity related to DT initiatives may demystify possible maritime ports' tenacity to go digital. Future research may investigate the role of prominent stakeholders—with mature DT initiatives in stimulating the implementation of DT in laggards. Other specific areas of interest include: (1) determining aspects of DT dimensions that require urgent implementation attention where a deeper analysis of singular dimensions and their nuances will be promising; (2) a deeper analysis of how individual port stakeholders' DT trajectories affect port ecosystem's holistic transformation endeavors and how these relationships can be empirically verified; 3) how collaborative agility can engender ports' ecosystems successful DT.

As DT is an evolving concept, to holistically understand its underlying tenets, further studies may examine the interplay of the factors in this study through quantitative and qualitative enquiries. Moreover, longitudinal research may robustly capture and clarify the interplay, e.g., moderating, mediating, or direct roles of the identified factors in the framework and address the gap between digital technological breakthroughs and organizational dynamics in implementing DT.

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