Literature Review on the Smart Port: Evolution, Technological Development, Performance Indicators of Smart Ports

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Abstract. Boost in the global supply chain in the post-industry 4.0 revolution has amplified the demand for maritime ports, triggering their operational capacities, competitiveness, and sustainability concerns. Maritime ports are undergoing a paradigm shift, an evolution from goods loading and unloading terminals to highly intelligent hubs in the logistic supply chain.

Existing literature on smart ports focuses on different aspects such as evolution stages, bibliometrics analysis, feasible technologies, and Key Performance Indicators (KPI).

This review complements the existing ones by investigating the term "smart port" definition, the technology use, the Key Performance Indicators (KPIs), and providing bibliometric analysis across major databases, sourcing from journals, conferences, official websites, and books in various disciplines.

Results show that the definition of "smart port" is still under development. Moreover, the major driver of transformation is the technology use, some technologies are mature enough for implementation and the rest are in the early stages. Importantly, along with innovative technologies, management skills play a crucial role in successful implementation. The Smartness of the port is difficult to answer but an accurate quantification of Key Performance Indicators (KPIs) can assist the ports in gauging their level of "smartness".

From the bibliometric perspective, there is a growing trend of smart port research, particularly in recent years. This trend is interestingly almost uniformly distributed in different geographic locations.

The findings underscore the kernel role of technology in shaping smart port evolution, and performance indicators for quantifying the smartness. The investigation of the challenges for ports to implement technologies is a key area for future research.

Keywords: Smart Port · Smart Port KPIs · Container Terminal Digital transformation · Industry 4.0 · Port Sustainability

1 Introduction

Ports are regional multimodal intersections of global supply chains (Molavi et al., 2020), a complex system that provides a logistic distribution hub for domestic and foreign trades, acting as a primary driver in the functioning of an open economy and social well-being.

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Maritime transportation accounts for 80% of goods carriage in the world, which makes it a vital part of the global supply chain (Belmoukari et al., 2023a; UNCTAD 2021). European ports in the third quarter of 2023 handled 807 million tons of goods (Eurostat 2023).

On the other hand, shipping is responsible for 3% of greenhouse gas emissions; an increase of 20% over the last decade has been observed, and no counteraction can cause a 130% shoot-up by 2050 to their 2008 level (UNCTAD 2023). These challenges are directly influencing the port's role in the industry. Environmental, business, social, and operational challenges for ports made governments, port authorities, and stakeholders rethink the operational design of the port. Port challenges are congestion, delays, operating errors, and lack of information sharing (Molavi et al., 2020). Issues related to the environment are water and waste management, energy demand and consumption, and their impact (i.e., noise pollution and greenhouse gas emissions), and safety and security issues (Belmoukari et al., 2023a). Moreover, ports are battling cutthroat competition due to their homogenization (Chen et al., 2019).

Therefore, the concept of smart port has evolved; it provides environmental compliance, financial efficiency, and technology support to ports. A smart port is, by definition, more connected, safe, and green. The term "smart" applies to more innovation in a competitive sense. Smart ports are more effective and offer greater performance. They provide real-time information and, an effective and collaborative management style. Successful technology involvement and a proper gauging of smartness through Key Performance Indicators (KPIs) are two essential elements of the transition from simple terminals to smart ports. Among the review studies available on smart ports, Li et al. (2023) laid a smart port foundation research on technologies used, and port performance indicators. However, how can smartness be defined for ports? Is a digitalized port smart? How can technology drive the ports to smartness? This research review tries to answer these questions, which include bibliometrics evolution stages of smart ports, technologies for ports, and Key Performance Indicators (KPI) and tries to elaborate on how these integrate for the development of smart ports.

This paper is organized as follows: the Sect. 2 analyses the bibliometric trends in smart port research, the Sect. 3 discusses smart port evolution and definition, Sect. 4 describes the literature on technologies for smart ports, Sect. 5 focuses on the key performance indicators for smart ports, and Sect. 6 is dedicated to the conclusion.

2 Bibliometrics

Bibliometric analysis was conducted using multiple approaches in the smart port area. Keywords such as smart port or smart ports, maritime ports, digital transformation, port sustainability, and container terminal were utilized. 76 articles were ultimately selected for synthetic analysis from 160 downloaded. The review includes 4 review papers and 69 novel experiments, case studies, reports, official websites, and books that advocate smart ports. VOSviewer software version 1.6.20, a tool developed by VN Eck and Waltman (2022) (Martins et al. 2022), was utilized for mapping keyword co-occurrence (Fig. 3), and data in RIS (Research Information Systems) format was extracted from Mendeley reference manager and used as VOSviewer's input. The concept of the smart port was

raised after 2010, nevertheless, we analyzed the papers from 2000 because of their technological involvement that founded the smart port concept. However, more weight was given to top journal papers (Table 1), bibliometric trends in publication years (Fig. 1), the geographic distribution of publications (Fig. 2), types of technologies for smart port and their use case (Sect. 4), macro and micro areas of key performance indicators, and contributing authors (Sect. 5). These are discussed as follows:

2.1 Annual Publication Trends

A positive trend has been observed in line with smart port research. The technological revolution and smart port development concept are key components of this tendency. Figure 1 shows publications from 2000–2023 in smart port. The graph shows a rapid development in recent years. 2020–2023 shows constant and maximum publications in the preceding years. It is noteworthy that exact smart port articles were found beyond 2016, and prior publications were somehow the building blocks and technologies that founded the smart port concept.

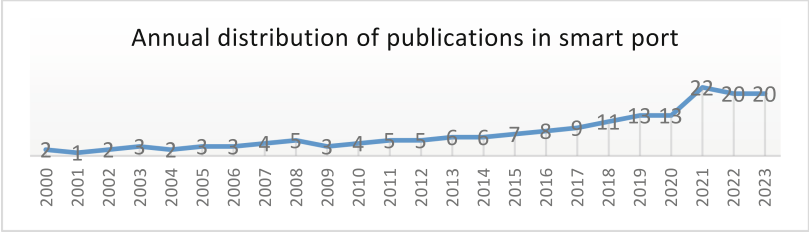

Fig. 1. Annual distribution of publications in smart port

2.2 Geographic Distribution

Interestingly, smart port research is distributed all over the world, as shown in Fig. 2. Europe and Asia have greater contributions. Specifically on smart ports, most research has been conducted in mainland China, with 16 publications, followed by Spain (11), Germany (8), Italy (7), Singapore (5), and Indonesia (5). The USA, Taiwan, Morocco, and Egypt have published 4, respectively. The UK, Thailand, Estonia, and Brazil contributed to 3 articles, respectively. Authors affiliated with France, South Korea, Russia, Poland, Croatia, and Belgium have each contributed to 2 articles on the smart ports area. Other nations, such as Vietnam, Ukraine, UAE, Turkey, Tunis, Srilanka, Portugal, Netherlands, Malaysia, Pakistan, Iraq, India, Greece, Finland, Slovenia, Canada, Chile, Bangladesh, Australia, and Albania have each one paper in the smart port domain.

Thus, smart port research is comparatively new, but the trend is growing uniformly throughout the world. The predominance of China in Smart Port Research could be due to the fact that China has the highest impact on global shipping and the special universities in China dedicated to maritime research e.g. Shanghai Maritime University

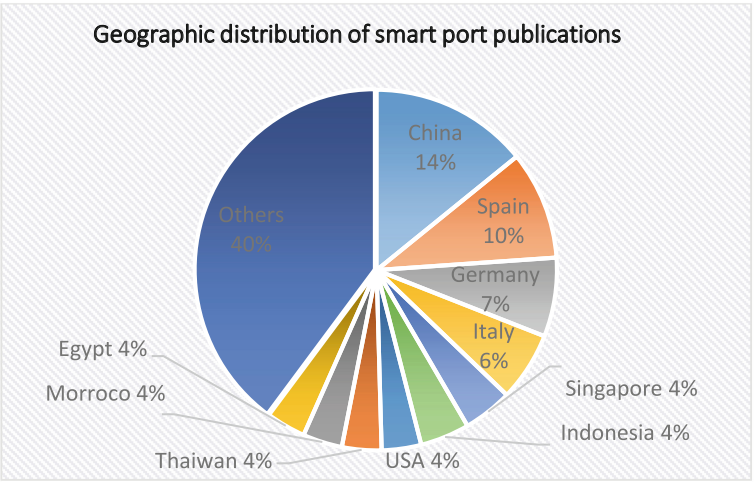

Fig. 2. Geographic Contribution to Smart Port Research

(SMU). It is noteworthy that this geographic quantification is based specifically on smart ports. Other areas that indirectly support smart ports i.e., use of technology in general transportation or supply chain, and research on ports in general are vast and not part of this spatial survey.

2.3 Top 10 Journals on Smart Port Research

Smart port research is a multidisciplinary field, maritime or marine journals, transportation-related journals, logistics, and technological or sustainability journals have an equal interest in smart port research. Table 1 lists the top 10 journals, out of 38, where smart port works are published more frequently. Thus, a selection of 24 out of 73 papers analyzed for this review are on this list.

Table 1. Top journals on smart port research

Journals	Publications
Maritime Policy & Management	4
Journal of Marine Science and Engineering	3
Sustainability	3
Environmental and Climate Technologies	2
Ocean and Coastal Management	2
IEEE Power & Energy Society General Meeting (PESGM)	2

(*continued*)

Table 1. (*continued*)

Journals	Publications
Case Studies on Transport Policy	2
Journal of Advanced Transportation	2
Logistics and Transportation Review	2
Ports and Network	2

2.4 Keywords Co-occurrence

The co-occurrence of keywords is a very useful tool to map the frequency of the occurrence of keywords within an article and the association of various topics. VOSviewer can illustrate this feature in clusters of keywords that represent the wholesomeness of the research topic. Figure 3 shows the keyword co-occurrence of this analysis. The map was created based on bibliometric data extracted from the Mandeley reference manager. The full counting method was selected, and a minimum number of occurrences of the keyword was taken as 2, given the fact that the port concept is very new and limited contributions are likely. Results show 74 items grouped in 12 clusters, with 204 links and a total link strength of 321.

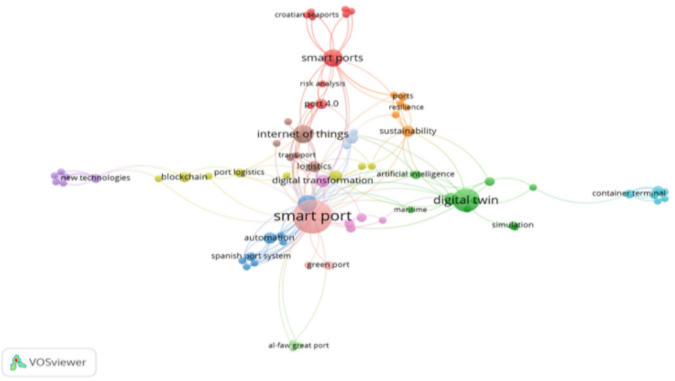

Fig. 3. Keywords Co-occurrence Map. VOSViewer (self-elaboration)

The sections described above deliver a clear idea of how smart port is injected into the research ground. The growing trend (Fig. 1) indicates the novelty of this discipline and its spreading trend, especially in the preceding years. Technological evolution (Sect. 4) is playing an important role in this trend. A very interesting part of this research is, that smart port research does not concentrate on a single geographic location but is widely distributed (Fig. 2). However, smart port indicators (Table 3) for a smart port may be different in various ports depending on many factors, such as education, environmental regulations, and the financial health of the port and country. In conclusion, the recent

and multidisciplinary nature of the smart port research area needs greater exploration, meanwhile making this area very interesting for further insights.

3 Smart Port Evolution and Definition

Smart ports are rooted in systematic, strategic, and social viewpoints that integrate modern technology use, constant interconnection, intelligent integration, coordinated operation, information sharing among interested parties, and creating an ecosystem that is smarter, safer, efficient, greener, flexible, resilient, and sustainable. Smart ports got the dominant attention for port development, representing the highest level of modern port transformation development, as reported by Chen et al. (2019). Currently, there are no universal definitions of what 'smart ports' are, since the 1990s, there has been an increasing trend for worldwide ports to invest in information and communication technology in operations (Du et al., 2023).

Yang et al. (2018) and Yau et al. (2020) defined smart ports as fully automated ports in which all devices are connected via IoT. Belmoukari et al. (2023b) define a smart port as a connected, sustainable, safe, and automated port, that relies on smart infrastructure and equipment, skilled personnel, and smart managerial practices to ensure customer satisfaction, environmental protection, and better quality of life for the citizen. Li et al. (2023) claim that smart ports enhance operational efficiency, communication, and crew satisfaction. Mi & Liu (2022) define the smart port as a system with cyber-physical systems as the structural framework, in which logistics suppliers and demanders are involved in the integrated system of collection, distribution, and transportation through the innovative application of high and new technologies. Smartness of ports can also be traced back to technology-driven automation and should be an integrated and coordinated system composed of knowledgeable and skilled work, intelligent infrastructure, automation, optimized port operations, enhanced productivity, energy efficiency, safety, and sustainability (J. Gao et al., 2022; Molavi et al., 2020b).

In this context, **five ports generation** may be distinguished by Yau et al. (2020):

First-generation ports were nodal points between sea and land and served as loading and unloading points for goods. *Second-generation* ports deployed equipment and infrastructures to reduce manpower dependency. *The third generation* provided value-added services such as warehousing, packaging, and distribution. *Fourth-generation* ports networked the physically separate ports. *Fifth-generation* ports, which are the latest version of ports, that provide services such as vessel and container management, are technology-driven by ICT and automation, connected, and integrated with the entire supply chain, and pursue sustainability goals. Jović et al., (2019) the transition process of ports towards smartness needs the mutual interest of governments and stakeholders.

In conclusion, it is quite evident from the above description that ports have evolved; indeed, traditional ports were just cargo loading and unloading terminals, and industrial ports were ports equipped with more advanced handling means, whereas smart ports are logistic nodes in which technologies have shifted the business into a service (Philipp, 2020a). The key driver of this transformation is technological evolution, as explained in the next section. Some technologies are mature enough for implementation, and some are at the research and development stage. However, a unified definition is still under

development, but the smart port concept revolves around the Key Performance Indicators (KPIs) described in Sect. 5.

4 Technologies for Smart Port

This section first synthesizes different technologies that may be implemented in a commercial port, then proposes an overview of the most significant case studies in which such technologies have been implemented. Finally, their effectiveness has been evaluated, followed by a discussion where various factors are examined for the successful implementation of technologies in the port industry.

4.1 Sensors, Internet of Things (IoT), and Digital Twins

Sensors are part of IoT-embedded systems that collect data such as temperature, and humidity, and structural health monitoring (SHM) for metal structures (Mi & Liu, 2020). Actuators work on the contrary, they take user input and trigger the system for action. Internet of Things, which consists of sensors, actuators, and embedded systems, is the foundation of smart ports (Bouhlal et al., 2022). Interconnection provides an excellent information-sharing platform among heterogeneous infrastructure and equipment. Digital twins in the port sector can be defined as a real virtual representation of a real scenario, which includes the actual layout of the system, design characteristics, and other relevant parameters. Cyber-physical systems and digital twins, integrated with IoT-embedded systems, could be used for the emulation or port operation for evaluation, prediction, and optimization of port systems (Rudskoy et al., 2021). Digital twin-based Q-learning algorithms are used to optimize the path planning for AGVs (Gao et al., 2022). The digital model is set with the desired algorithms; it generates instructions through fitted actuators to trigger the physical system, which is subjected to human intervention. Szpytko & Salgado Duarte, (2021) presented a model capable of organizing the maintenance scheduling strategy in the container terminal. Researchers such as Lind et al. (2020), Kirchhof et al. (2021), Y. Zhou et al. (2022), Wang et al. (2021), and Skuba & Janota. (2020) also studied digital twins for ports.

4.2 Information and Communication Technologies (ICTs) and 5G

ICTs can reduce the delay due to documentation and enhance transparency and trust (Kapkaeva et al., 2021). The IT-supported system uses modern technologies for efficient information flow throughout the entire transport supply chain. Information systems consist of data acquisition devices, data centers, and networking and communication (Yau et al., 2020). 5G technology is 100 times faster than 4G, this quick transition of data leads to lower power consumption and provides support for IoT. Sohaib et al. (2021) highlighted automated rail-mounted gantry cranes that have recently been deployed at Singapore's Pasir Panjang Terminal 5, where cranes can stack containers 6 high and 10 broads. Up to five cranes may be under the control of one operator from the control room. These cranes increase production by over 10% by moving more than 30 containers per hour; improved safety is a side benefit of the increase in production.

4.3 Artificial Intelligence (AI)

Artificial intelligence is used for programming machines to replicate and imitate human decision-making and monitoring processes. AI, through machine learning, uses big data to predict the future scenarios of operations and logistic chains. AI is used for the estimated time of arrival (ETA), and the average reliability of a global carrier arriving on time across 34 different trade lines fell to 50.1% ('Report Sea-Intelligence', 2020). da Silva et al. (2023) used a machine learning algorithm to study dynamic scheduling for the Truck Appointment System (TAS) at the gate, achieving 95% accuracy, a 90.4% improvement in truck waiting time, and an 80% reduction in the entrance queue.

4.4 Blockchain

Blockchain-based applications provide transparent visibility of information to involved parties to build trust reduce interdependency and reduce the chance of fraud and tampering inside the chain by disintermediating the traditional chain and enhancing end-to-end process visibility. Giant corporations such as MAERSK and IBM applied blockchain technology by introducing TRADELENS, which involves broader supply chain insight, not limited to shipping activity (Kapnissis et al., 2022). It is applicable to document exchange, cargo tracking, and tracing. Paperwork in the shipping industry is responsible for 15%–50% of transportation costs. Blockchain technology can replace those hassles by providing a paperless environment (Yau et al., 2020).

4.5 Computer Vision Application for Container Identification

For administration in terminals, yards, and customs, serial numbers are the fundamental information about containers. Computer vision can be used to automatically recognize a container's number and collect this data as part of automatic real-time logistics, resolving the crucial problem of automated container management as it is practiced in several Chinese ports (Yang et al., 2018).

4.6 Automation

The primary drivers for port automation are enhancements in operational effectiveness, reduction in the per container handling cost, the shift from labor to capital costs, increased land productivity, increased environmental sustainability, safety, and security, and application of cutting-edge technology (Rodrigue & Notteboom, 2021). Shanghai Yangshan Port Phase IV is a fully automatic port except few operations (Luo, 2019).

4.7 Cyber Security of Smart Ports

Interconnected physical systems with digital technology in cyberspheres leave crucial security risks; thus, a cyber security plan is an essential component of smart ports (Yau et al., 2020). Cybersecurity skill shortages in ports are one of the critical vulnerabilities for cyber attackers. Data infrastructure needs a concrete security architecture in the port support system. Cybercriminals may target data-rich integrated electronic platforms,

such as systems related to Maritime Single Windows (MSW) and Port Community Systems (PCS) (Tusher et al., 2022). New methods of hardware hacking in barcode scanners and other equipment are utilized to launch cyber-criminal activities in port operations, in addition to security flaws in radio transmission and software. Integrated systems of devices, agents, and activities and a holistic ecosystem of connectivity inside smart ports have raised the cyber risk (de la Peña Zarzuelo, 2021).

4.8 Technology Use-Success Examples

Technology is practiced in many ports around the world. The Valencia port uses an LED lighting system, and 73% less electricity consumption is recorded since devices only illuminate when vehicles are nearby (Valencia port). Port of Rotterdam (Digital Report) showed digitalization of customs documents reduced processing time by 30%, and the OnTrack application resulted in a more accurate Expected Time of Arrival (ETA) of ships, which is a major issue for terminal operators. Port of Gdynia, Poland uses the navigation tool developed by NavSim (Navigation). Port of Gothenburg utilizes a bunkering App that synchronizes the bunkering data, which is incredibly useful for operators to plan and execute bunkering operations (Bunkering App). Port of Antwerp uses sensors to measure the tension on the bollard (Port of Antwerp), the Port in 2017 installed devices, called iNose for measuring and monitoring the air composition (Port of Antwerp-Bruges). In addition, Limas et al. (2022) in their case study on the Port of Balikpapan found that minimal technology use in ports causes inefficient operations. Triska et al., (2019) studied smart port-hinterland integration using 5 Brazilian ports, substantiating that smart port logistics systems enhance the reliability and efficiency of port-hinterland integration, minimizing disruption throughout the supply chain. It contributed to a reduction of at least 78% in the truck queues at the analyzed ports. Llaha & Rista (2021) recommended implementing Vessel Traffic Service (VTS) and Vessel Traffic Management Information Service (VTMIS) systems as the "Single Window" with the help of blockchain and IoT, establishing a communication hub among stakeholders in Albanian ports. Ortiz et al. (2022) worked on an IoT microservice architecture for air quality monitoring and alerting in smart ports. Jin, (2023) suggests a selection of virtual team members for smart port development projects. Jun et al. (2018) used a combination of Delphi surveys and input-output analysis to evaluate the impact of the smart port industry on the Korean economy, and a field survey was carried out. Jović et al. (2019) studied ICTs for port efficiency. Rüßmann et al. (2015) summarized nine technological advancements in industry that paved the foundation for further research and development. To summarize the analysis performed in Sect. 4, various technologies explored by the authors have been clustered. However, some technologies have proven success (i.e., automation and ICTs) and few (i.e., augmented reality and blockchain) are at an infant stage for industry use (Table 2).

Table 2. Technologies explored by various authors.

Area	Authors
Internet of things (IoT)	Rüßmann et al. (2015), Li et al. (2023), Muñuzuri et al. (2020), Bouhlal et al. (2022), J. Gao et al. (2022)
Artificial intelligence	Rüßmann et al. (2015), de la Peña Zarzuelo et al. (2020), da Silva et al. (2023)
Automation	Li et al. (2023), Rodrigue & Notteboom (2021), Luo (2019), Zhao et al. (2021), Rüßmann et al. (2015)
Cyber security	Rüßmann et al. (2015), de la Peña Zarzuelo et al. (2020), Li et al. (2023), Yau et al. (2020)
Bigdata	Li et al. (2023), Rüßmann et al. (2015)
Simulation modeling	Rüßmann et al. (2015), de la Peña Zarzuelo et al. (2020)
ICTs	Molavi et al. (2020), Yau et al. (2020), Kapkaeva et al. (2021), Yang et al. (2018)
Additive manufacturing	Li et al. (2023)
Blockchain	Kapnissis et al. (2022), Yau et al. (2020), de la Peña Zarzuelo et al. (2020)
Digital twins	Szpytko & Salgado Duarte (2021), Wang et al. (2021), Szpytko & Salgado Duarte (2021), Lind et al. (2020), Kirchhof et al. (2021), Skuba & Janota (2020), Y. Zhou et al. (2022), Y. Gao et al. (2022), Rudskoy et al. (2021)
Machine vision	Yang et al. (2018)
5G	Sohaib et al. (2021)

5 Key Performance Metrics

In addition to technological aspects, another important part of the literature is devoted to key performance indicators. Successful implementation of technology is a primary pillar of "smart ports". An important reference is the "Port Performance Measurement," derived from the "United Nations Conference on Trade and Development" (UNCTAD-1976), from where the Port Performance Indicators originated (Philipp, 2020a). Traditionally, Port Performance Indices were mainly focused on operational efficiency and the annual throughput. However, the recent digitization revolution added novel indicators (Ha et al., 2019). Due to the rising interest in digitalization, the recent Port Performance Measurement (PPM) concept exhibits novel indicators like IT systems, databases, networks, integrated Electronic Data Interchange (EDI) for communication, and integrated IT to share data. Smart Port Indicators (SPIs), derived from Port Performance Metrics, refer to measuring tools that indicate port performance in terms of several operational, environmental, energy, security, functional, and social domains. Numerous research efforts have been conducted to assess smart ports from one or more perspectives. Iris & Lam (2019) indicate the ecological environment such as energy consumption, renewable energy, and water pollution, as primary parameters for smart ports. According to Gunes et al.

(2021), technological environments such as digital transformation, cyber security, and operation infrastructure are smart port indicators. Policy environments such as port-city integration, policy support, and cooperation with government departments are studied by D'amico et al. (2021). The education level of the workforce, logistic services, and production management were discussed by Meyer et al. (2021). Philipp (2020b) established a readiness index assessment for smart port development. Table 3 summarizes key authors who specifically studied Key Performance Indices of smart ports clustered by domains.

Table 3. Authors contributions in key performance domains and metrics

Domains	Indicators	Authors
Operational	Agility & Resilience and Operational efficiency	Molavi et al. (2020), Chen et al. (2019), Bichou & Gray (2004), Li et al. (2023)
Energy	Consumption	Iris & Lam (2019), Battino & del Mar Muñoz Leonisio (2022),(Gervasi et al. (2022)
Ecological Environmental	Water	Iris & Lams, (2019), Molavi et al. (2020), Battino & del Mar Muñoz Leonisio (2022), Gervasi et al. (2022)
Technological Environment	Cyber security, Operational infrastructure	Gunes et al. (2021), Philipp (2020b), Ha et al. (2019), Chen et al. (2019), Du et al. (2023)
Policy Environment	Port-city integration; Policy support, Collaboration with environment department	D'amico et al. (2021)
Education & Training	Workforce education	Meyer et al. (2021)
Logistic Services		Meyer et al. (2021), Chen et al. (2019),
Management	Productional management, Crew, and Customer satisfaction	Meyer et al. (2021), Belmoukari et al. (2023b), Li et al. (2023)
Safety and Security		Molavi et al. (2020), Battino & del Mar Muñoz Leonisio (2022), Chen et al. (2019)
Socioeconomics	Quality of life for citizen	Battino & del Mar Muñoz Leonisio (2022), Gervasi et al. (2022), Chen, Xue, et al. (2019)

Molavi et al. (2020) assessed port performance indicators in five aspects: operation, environment, energy, safety, and security. According to D. Zhou et al. (2022), the indicators are mainly composed of eight categories: market, technology, production,

finance, service, manpower, and safety production supervision and inspection. Chen, Xue, et al. (2019) categorize the smart port evaluation indicators in the following major domains: port production and operation system, port financial, port logistic supply chain system and trade service technologies, port energy conservation, and emission reduction capacities. Makkawan and Muangpan (2021) identified the SPIs and developed a conceptual model of port performance using the subject of Thailand's Eastern Economic Corridor (EEC) in 29 indicators. Lakhmas & Sedqui (2020) and Maglić et al. (2021) surveyed 78 marinas to understand their level of smartness using KPIs. The Port of Hamburg and Singapore are good examples of ports as smart, developing economic, social, and environmental improvement (Rajabi et al., 2019). Hsu et al. (2023) studied the service quality of smart ports' key factors for success during the post-pandemic era, SERVQUAL service quality scale 25 evaluation indicators. Jun et al. (2018) studied the impact of the smart port industry on the Korean national economy using input-output analysis. Chen et al. (2019) applied a single-valued neutrosophic exponential similarity measure to enable quantitative evaluation of port integrity for setting smart port KPI. Wu et al. (2010) analyzed the model to test the sensitivity of the individual input and output of a decision-making unit (DMU), results indicated the number of berths, investments, and location of the container terminal are fundamental for performance. Campisi et al. (2022) in their case study on the port of Ravenna, Italy, stressed a locally integrated partnership framework. Botti et al. (2017) studied Salerno port and found port as a smart service system through the lens of service science.

Pham (2023) studied the indicators, and challenges of smart port development. Li et al. (2023) studied available publications on smart ports from 2002 to 2021. However, the actual research on smart ports began after 2010. Studies and reports indicate that the primary driver of smart port evaluation is the increasing involvement of technology. However, as described in Sect. 4, numerous factors guarantee the successful implementation of technology in the port.

In conclusion, Key Performance Indicators are not just a measure of port efficiency but a strategic move that leads to optimization of operations, sustainability, and maritime logistics enhancement. Technology implementation is a crucial figure in performance indicators, but it's not the whole picture of performance. Interestingly, KPIs can be defined in a customized way; a parameter that is crucial for one port may not be for another. A port can achieve a maximum level of its own set of KPIs, but in this case, significant metrics such as sustainability cannot be ignored. Finally, all the above-described KPIs serve the port to gauge their level of smartness, guiding the port industry towards resilience and innovation.

6 Discussion and Conclusion

Maritime ports are crucial actors in the global economy. However, associated environmental, operational, social, and safety concerns in the port industry have gained prominence in recent years. These challenges made the terminal operators and authorities rethink on operational design of the port. Therefore, the smart port concept emerged. This research revealed the emerging trend of smart port research, a shoot-up in publication has been observed in recent years (2021–2023) uniformly distributed throughout

the globe. Maritime Policy & Management, Journal of Marine Science and Engineering, and Sustainability were the top three journals with 4, 3, and 3 publications respectively. Smart port(s) was the most used keyword in literature, followed by digital transformation and the Internet of Things.

The growth and success of a smart port depend on several factors, most of them not depending on the technologies but on where, how, and when they are implemented and integrated. However, some indications explained in Sect. 5 highlight the key success elements that enable the growth of smart ports. Philipp (2020a) studied the readiness of port smartness, concluding that the current strategic position and benchmarking the measurement induces are dominant factors. Only innovative technologies do not safeguard digital transformation, but management measures, knowledge, and skills play important roles. Heilig et al. (2017) highlighted the role of digital transformation in ports since it will make it possible to inter-, intra-, and meta-organizational dimensions, but pointed out that digital initiatives cannot succeed in obtaining their purpose if the customized requirements of individual actors are not properly addressed in seaports. According to Castellano et al. (2019), Investments in Digital communication Technologies (DCTs), asset efficiency monitoring (DEA), and port competitiveness improvement are three crucial success elements that enable the growth of creative smart ports as *The Port of the Future*. Finally, it has been widely demonstrated the need to invest massively in digital data-based technologies should be extended to the whole logistic chain and, thus, also to smaller ports that are often either reluctant or limited in their knowledge (Philipp, 2020a). In these streams, digital transformation is fundamental for the strategic alignment and cooperation among stakeholders. However, it is the attitude, management skills, stakeholders' motivation, and vision that guarantee the success of digital transformation.

In conclusion, the recent development and multidisciplinary nature of the smart port research needs greater exploring, meanwhile, it makes this area very interesting for further investigations. Our analysis delved into smart port definition and evolution. Findings suggest that smart port definition is still under development due to technological evolution but a set of KPIs helps to figure out the concept. Technology plays an important role in ports' transformation from traditional terminals to smart ports. However, the growth and the success of a smart port rely on numerous factors, most of them not depending on the technologies, but on where, how, and when they are implemented and integrated. Some successful examples of European ports (i.e., Port of Antwerp, Rotterdam, and Hamburg) have shown very positive results such as minimizing custom processing by 30% in Rotterdam and Port of Valencia reducing energy consumption by 78% after installing light systems sensors. One of the important areas of smart ports explored in this study is the Key Performance Indicator (KPIs). These indices refer to measuring tools that indicate port performance in terms of several operational, environmental, energy, security, functional, and social domains. KPIs are very useful sets of metric ports that can be used to gauge their level of smartness, not only economic, and operational boost but enhancement in whole port logistics and sustainability.

This research insights into the useful understanding of smart ports definition, feasible technology, use-cases, factors for successful implementation, and KPIs to gauge the level of smartness.

Practical applications of smart port measures still lacking in medium and small-size ports around the world. A study that evaluates the challenges and barriers terminal operators face in implementing these measures is worth exploring.

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