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Smart ports for sustainable shipping: Concept and practices revisited through the case study of China's Tianjin port

Abstract

The development of smart ports is digitally transforming shipping and logistics operations, paving the way for a more sustainable shipping paradigm. Research has begun exploring this burgeoning field from diverse perspectives, from technological advancements to evaluation methodologies. Nevertheless, more research is needed on the smart port concept to gain insights into the practices and evaluation. We fill the knowledge gap by applying *population ecology* theory to revisit the smart port concept. The port of Tianjin is used as an illustration. By leveraging policy documents, industry research, company annual reports, and corporate social responsibility reports, we analyze the key stakeholders in the smart port ecosystem, their relationships, the system's evolution, and the cargo and information flows within the smart ports, drawing analogies to the ecological concepts of components, relationships, evolution, and flows. Based on these findings, we revisit the smart port concept from an ecological perspective. We also introduce the ecological concept of "health" into evaluating smart ports. "Health" in this paper underscores evaluating their implementation progress (i.e., the varied pace of smart port development), overall stability (i.e., ability to maintain stable operations amid external uncertainties), and readiness for fully-fledged operations. This concept is operationalized through a novel evaluation framework comprising four first-level indicators (Vitality, Coordination, Development, and Growth) and 12 second-level indicators, enabling managers to identify their smart port's development status and areas for improvement actions.

Keywords: Smart port evaluation, Smart port concept, Smart port health, Sustainable shipping, Best-Worst Method (BWM)

Shipping facilitates most of the international trade volume, and seaports, as cargo hubs, are indispensable in maritime transport (Lun and Marlow, 2011). The level of port development can indicate a country's economic development (Zhao et al., 2023). With the easing of COVID-19 globally, the world economy is picking up resiliency, and international trade activities have once again become intense, both in volume and frequency, causing stress to ports' operational capacity. Ports require urgent operational transformation and upgrading to handle larger ships, supply chain integration, and sustainability challenges (Notteboom and Neyens, 2017). Countries continuously embark on port upgrading. China, for example, has set guidelines for building world-class ports; the Maritime and Port Authority of Singapore operates under the *Next Generation Port Plan 2030* (NGP2030); and the Port of Hamburg focuses on smart logistics and energy. Integrating AI and emerging technologies into ports (Schwab, 2017) and transforming them into Smart Ports or Port 4.0 (de la Peña Zarzuelo et al., 2020) presents a promising avenue to enhance port resilience (Boullauazan et al., 2023), efficiency (Yen et al., 2022), and sustainability (Molavi et al., 2020). Such upgrades enhance the efficiency of port operations and equip ports with efficient response mechanisms to disruptions, ensuring they remain robust amidst escalating global uncertainty.

Upgrading ports means transitioning to smart ports, which evolve from traditional ports by incorporating high-tech technologies (Li et al., 2023). Such evolution leads to the automation and intelligence of the entire operational process, thereby enhancing ports' efficiency, safety, and environmental standards. Various ports worldwide, such as Tianjin Port, Shenzhen Mawan Port, Xiamen Port, and Rotterdam Port, are continuously developing into smart ports. Tianjin Port, and Shenzhen Mawan Port have already announced the completion of smart ports. Although automated terminals have already improved efficiency, the transformation into smart ports through technological empowerment brings more tangible benefits, notably reduced energy consumption and labor costs. For instance, Tianjin Smart Port has achieved a 60% reduction in personnel and a 50% decrease in the container operation transshipment process. This enhancement has led to an operational efficiency of up to 39 TEUs per hour, which represents more than a 17% energy saving compared to fully automated ports in operation today and a 30% reduction in investment relative to automated container terminals with the same shoreline (Tianjin Municipal People's Government, 2021). Meanwhile, Shenzhen Mawan Smart Port's implementation of a green, low-carbon system is estimated to reduce nitrogen dioxide emissions by approximately 1350 tons, carbon monoxide emissions by around 450 tons, and sulfur dioxide emissions by about 15 tons annually (Department of Transport of Guangdong Province, 2021).

We need a clearer consensus on understanding and defining "smart ports" (Molavi et al., 2020; Triska et al., 2022). Much of the existing research on smart ports adopts a "technology-feature-function" framework. For example, Chen et al. (2019b) consider smart ports adopting next-generation information technology to achieve all-around sensing, intelligent integration, and other functions, and enhance their security, flexibility, and green development capabilities. However, the scope of their analysis is limited to the internal operations of ports, such as unloading containers from ships to yards and their subsequent transportation to destinations outside the port area.

A potential point of confusion is the distinction between automated terminals and smart ports. The former operate automatically without human intervention (Jia and Cui, 2021), which does not necessarily make them smart ports. The nuances and relationships between these concepts warrant further investigation.

Is technology core for smart port development? Who develops port technology, and who invests in the development of smart ports? The evolution of smart ports hinges on integrating advanced technology and the seamless sharing of information related to cargo, trade, vessels, and operations. These elements are undeniably pivotal for the successful realization of smart ports. However, a deeper exploration is required to identify the various stakeholders and delineate their specific roles in the implementation process. Grasping these intricacies is essential, especially against the backdrop of the rapid advancements of Industry 4.0 and the escalating competition among ports (Panahi et al., 2022).

The journey towards smart ports is not a solo endeavor; it demands collaborative efforts and substantial investments from diverse entities (Barona et al., 2023). For instance, the collaboration between Tianjin Port and Huawei Technologies Co., Ltd. exemplifies the synergy between port authorities and tech giants, resulting in developing a Level 4 autonomous driving system for port transportation.[1] On the policy and investment front, the Shenzhen government's initiatives to foster smart ports highlight the role of governmental bodies in shaping the future of ports. Yet, as seen in the Mawan Smart Port project by China Merchants Group, with its staggering 4.37 billion RMB budget, the sheer scale of investment underscores the indispensable support required from financial institutions (Shenzhen gov., 2021).

We find that natural ecosystems are inextricably linked to smart ports, so we adopted an ecosystem perspective to deconstruct the intricate relationships in smart ports. Doing so is also a great attempt to utilize the ecological perspective[2] in port management.

To strive for world-class operations in smart ports, developing a scientific and objective method for evaluating implementation is desirable (Krmac et al., 2022). On January 12, 2022, China Ports Association released their "guidelines for rating evaluation of smart port - container terminals" (T/CPHA 9-2022). The guidelines put forward general requirements, evaluation framework, and evaluation elements for the smart port rating of container terminals.

Extant literature assesses smart ports from various perspectives, including those of sustainability (Chen et al., 2019b), port operations (Gonzalez et al., 2020), and logistics operations (Liu et al., 2022). These perspectives allow the evaluation of the current state of smart ports, such as the extent of technological advancements in smart port infrastructure. Smart ports, which are primarily experimental at this stage, are still in the throes of development. Evaluating their implementation progress (i.e., the varied pace of smart port development), overall stability (i.e., ability to maintain stable operations amid external uncertainties), and readiness for fully-fledged operations—referred to in this context as their "health"—is important for research and practice. A smart port evaluated as "healthy" means developing and performing optimally, achieving its expected operational efficiency, technological advancements, and sustainability targets. One example is Tianjin Port, which has shown exemplary performance across various health indicators, including effective cooperation with numerous companies and institutions and a strong capability for innovation (Tianjin Municipal People's Government, 2021). This led to the rapid establishment of its smart port infrastructure and the initiation of operations within just 21 months (Central People's Government of the PRC, 2021). However, the global transformation to "smart" status remains limited among ports. Assessing the health of smart port implementation is pivotal, as it provides insights into the potential success of such developments. Port management must have objective key performance indicators (KPIs) to evaluate how well smart ports perform and plan improvement actions (Mendes Constante et al., 2023).

This paper examines the health of smart port implementation based on population ecology theory (Amburgey and Rao, 1996; Hannan and Freeman, 1977). The theory emphasizes the diversity and adaptability of organizations to formulate the stage change and development process. It focuses on the organizational level as the unit of analysis to explain the relationship between organizations and their environments.

[1] According to the Society for Automotive Engineers (SAE) (2021) classification, autonomous driving is categorized into levels 0 to 5, ranging from fully manual to fully automated. Level 4 denotes a system that operates without human intervention in most situations yet allows for human intervention in case of problems or failures.

[2] Ecology is a scientific discipline investigating the interrelationships among organisms and their interactions with the environment. It examines ecosystems' structure, function, and dynamic processes and explores how biological populations adapt to and respond to environmental changes. Applying concepts from natural ecosystems enhances our comprehension of various systems, including their composition, flows, and evolution (Pickett et al., 2010).

We draw on the why-what-how research process (Edler and Fagerberg, 2017) to:

1) examine smart port implementation as an ecosystem and determine its components. This mainly includes subjects related to the development and operations of smart ports, such as government departments and technology companies.

2) identify the role of these elements in a smart port scenario and explain their impact on the smart port implementation and

3) construct a framework for evaluating the health of smart ports.

The research contributions of this paper as follows: First, we adopt an ecological perspective in our study. This lens illuminates the complex and interdependent relationships among the various entities creating and operating smart ports. This approach provides a comprehensive understanding, allowing us to identify the roles and interactions of different stakeholders within the smart port ecosystem. Our research has identified critical factors driving the health of smart ports evolution. Based on these factors, we propose an evaluation framework for evaluating smart port implementation.

Second, our study is grounded in a successful implementation case: the Tianjin Smart Port, a technology demonstration project under the aegis of the Ministry of Transport of China. This project underwent on-site verification by Ministry of Transport experts on March 17, 2023 (Ministry of Transport of the PRC, 2023). The evolution of the Tianjin Smart Port has undergone significant phased transitions, offering valuable insights into the progression of smart port implementation. A complementary relationship exists among the components involved in the development and operations of Tianjin Smart Port, which can be further examined from an ecological perspective. This study can help managers and policymakers to better design smart ports, and to develop processes to accelerate smart port development.

The rest of the paper is structured as follows. Section 2 provides a review of the literature on smart ports. Section 3 relates smart ports to ecosystems and understands smart ports from the ecosystem level. Section 4 details the evaluation framework's construction and the weight determination process. Finally, Section 5 presents pertinent recommendations and concludes the study.

2. Literature review

Research on smart ports can be broadly categorized into two main areas. The first pertains to the conceptual framework of smart ports. This area is still in its nascent stages. It predominantly revolves around identifying the technologies integral to smart ports (Min, 2022), delineating the role of smart ports (Botti et al., 2017), and characterizing their distinct features (Xiao et al., 2022). The second area delves into the evaluation framework of smart ports. Numerous scholars have developed these indicators, each approaching from unique perspectives (Chen et al., 2019a, 2019b; Hsu et al., 2023; Alaa Othman et al., 2022).

2.1. Conceptual framework of smart ports

In identifying technologies for smart ports, Min (2022) argues that smart ports were developed based on a Cyber-Physical System (CPS), integrating computing, communication, and control technologies. D'Amico et al. (2021) refined the definition of smart port technology, including new-generation technologies such as the Internet of Things (IoT), sensors, cloud computing platforms, and smart grid technologies. de la Peña Zarzuelo et al. (2020) also considered IoT and sensors, big data business analytics, and augmented reality technologies as the pillars of Industry 4.0 and the foundation for smart port development. These technologies were crucial for developing and operating smart ports, as they provided the foundation for the role and functionality of smart ports, such as improving transportation efficiency and promoting sustainability. For instance, the Mawan Smart Port in Shenzhen has deeply integrated cutting-edge technologies such as 5G and artificial intelligence into its operations, resulting in a 45.4% increase in yard efficiency, a 50% improvement in gate efficiency, and a 90% reduction in carbon emissions compared to pre-transformation levels (Department of Transport of Guangdong Province, 2021).

Works have focused on the positive impact of smart ports on society, the economy, and the environment. Regarding the role and function of smart ports, Yau et al. (2020) asserted that smart ports significantly improved ship and container management, thereby enhancing the competitiveness and sustainability of national economies. D'Amico et al. (2021) suggested that smart ports have the potential to contribute to economic, environmental, social, and technological mobility. Chen et al. (2019b) argued that smart ports reduce daily port production costs, promote efficient production, enhance risk mitigation, and meet long-term development requirements. Jun et al. (2018) identified the substantial impact of smart ports on productivity, value-added, and employment. Yen et al. (2022) also believed that smart ports could save energy and manage environmental impact for sustainable development. However, the benefits of a smart port take time to emerge and, at its early stages, the development of a smart port can be more energy-consuming and inefficient than that of conventional ports. Avoiding these problems has been a significant challenge in the industry, requiring participants in smart ports to work together to build and operate them, leveraging feedback, cooperation, and synergy. For example, when developing smart port digital twin technology, the Port of Rotterdam initially collaborated with IBM, Esri, Cisco, and Axians to develop a cloud-based Internet of Things platform (Port of Rotterdam, 2018).

Similarly, during the development of the smart port demonstration project at the Qingdao Port, the port collaborated with Huawei Technologies Co., Ltd. to fully leverage Huawei's advantages in 5G and cloud computing (Huawei Technologies Co., Ltd., 2019). These examples highlight the importance of cooperation among various stakeholders in developing and operating smart ports, enabling them to overcome challenges and realize the full potential of these innovative initiatives.

Concerning smart port characteristics, Heikkilä et al. (2022) considered automation, sustainability, and collaboration as the defining ones, while Philipp (2020) highlighted security, process optimization, and sustainability. These characteristics align with China's new development concept of "innovation, coordination, green, openness, and sharing" for ports and meet the International Maritime Organization's (IMO) green port development requirements. For these goals to be achieved, a sound evaluation framework is crucial to provide a reference for smart port development.

2.2. Evaluation framework study of smart ports

Research has seen indicator-based evaluation frameworks. Such frameworks typically comprise a set of quantitative and qualitative indicators that evaluate various aspects of port operations, including efficiency, environmental impact, and socio-economic benefits. For instance, the "Guidelines for rating evaluation of smart port - container terminals" developed by the China Ports & Harbours Association arise from the need to address disparities in regional development and the lack of uniform technical standards. This framework clearly defines the direction and objectives for smart port development, providing a standardized approach to evaluate and enhance the efficiency, sustainability, and integration of smart technologies in port operations (China Ports & Harbours Association, 2022). Most of the studies were conducted on container ports; this happens because container ports have the highest level of smart operations at this stage. Besides this, Zhao et al. (2020) investigated the sustainable development path of coal ports in three dimensions: economic, environmental, and social. Their results showed that adopting smart technology, although increasing operational costs in the short term, will bring considerable economic benefits and social impacts for the ports in the future.

Regarding qualitative research, indicator-based frameworks are developed for sustainability, technology, maturity, and digitalization levels. Alaa Othman et al. (2022) proposed a Smart Port Index (SPI) based on the literature in five areas: environmental, operational, safety and security, human, and energy, considering sustainability and human resources. Boullauazan et al. (2023) developed a smart port maturity model by reviewing the literature that can be used to assess the maturity level of smart ports. Philipp (2020) developed a digital performance evaluation framework for smart ports, which includes five first-level indicators: Management, Human Capital, Functionality (IT), Technology, and Information. Hsu et al. (2023) proposed six elements of smart port success in the post-epidemic era. Wang et al. (2021) elaborated on the relationship between *digital twin* (DT) and smart ports and proposed applications and challenges for DT-driven smart port management.

We reviewed the existing indicator-based frameworks to identify commonalities and differences. We chose ten representative papers, ensuring each met two key criteria: they were published within the last five years and had constructed a specific evaluation framework for smart ports. Considering the importance of official standards issued by professional institutions, we have also selected the evaluation criteria issued by the China Ports & Harbours Association and the China Institute of Navigation to enrich our review. We have placed information from these two organizations and their published smart port evaluation frameworks in Appendix B. The list of these studies appears in Table 1.

Table 1. List of literature containing evaluation framework of smart port

No.	Author	Literature Title	Year	Literature Resource
A	Chen et al.	Simplified neutrosophic exponential similarity measures for evaluation of smart port development	2019	Symmetry-Basel
B	Liu et al.	Research on the Beibu Gulf port container terminal operation system construction performance evaluation based on the AISM-ANP	2022	Journal of Marine Science and Engineering
C	Gonzalez et al.	Preparation of a smart port indicator and calculation of a ranking for the Spanish port system	2020	Logistics
D	Hsu et al.	Key factors for the success of smart ports during the post-pandemic era	2023	Ocean & Coastal Management
E	Yen et al.	How smart port design influences port efficiency – A DEA-Tobit approach	2022	Research in Transportation Business and Management
F	Lin et al.	Exploring the impact of different port governances on smart port development strategy in Taiwan and Spain	2022	Sustainability
G	Philipp	Digital readiness index assessment towards smart port development	2020	Sustainability Management Forum
H	Xiao et al.	Digital empowerment for shipping development: a framework for establishing a smart shipping index system	2022	Maritime Policy & Management
I	Molavi et al.	A framework for building a smart port and smart port index	2020	International Journal of Sustainable Transportation
J	Li et al.	Smart port: A bibliometric review and future research directions	2023	Transportation Research Part E: Logistics and Transportation Review
K	China Ports & Harbours Association	Guidelines for rating evaluation of smart port - container terminals	2022	China Association
L	China Institute of Navigation	Evaluation indices for intelligent ports	2023	China Association

We organized the first-level indicators from the evaluation framework for smart ports, as mentioned in the preceding literature, into nine categories. Table 2 shows that the serial numbers A-L correspond to the references. We conducted a statistical visualization analysis to present the classified indicators. In Fig. 1, the orange bars indicate the total occurrence count of each category's first-level indicators across all considered literature. This means that if the same reference's first-level indicator occurs multiple times under a category, we accumulate the counts. The blue bar represents the number of literature included under this category. If literature has many first-level indicators under this category, we only accumulate them once. This approach allows us to distinguish between the breadth of literature support for each category (as shown by the blue bars) and the depth or frequency of discussion concerning specific indicators (illustrated by the orange bars).

Table 2. First-level indicators statistics

No.	Indicator Category	Description	First-level indicator in literature
1	Sustainability	Relates to environmental health, conservation practices, and long-term ecological viability. Emphasizes green practices, energy efficiency, and environmental protection.	Port energy conservation and emission reduction capacities [A], Green and safety [B], Environment [C][E][I], Environmental protection [F], Energy sustainability [F][I], Ecological environment [J]
2	Finance and trade	Focuses on economic aspects, including financial services, cost-effectiveness, and trade-related benefits.	Port financial and trade service technologies [A], Costs and benefits [B]
3	Port operations	It encompasses core functional and operational aspects, reflecting efficiency, service quality, and overall operational health.	Port production and operation systems [A], Loading and unloading operations [B], Service capability [B], Operational economic [C][F], Assurance[D], Production operations [H], Operations [I], Business units [L], Port service levels [J]
4	Logistics operations	Targets logistics and supply chain components, gauging the efficiency of movement and storage of goods.	Port logistics supply chain system [A], Chokepoint operations [B]
5	Society, culture, and politics	Evaluates the port's impact on and alignment with societal values, cultural contexts, and political frameworks. This category gauges the port's integration with community needs and adherence to policy and institutional requirements.	Social [C], Political and institutional [C], Community service [F], Policy environment [J]
6	Smart technologies and automation	Delves into technological advancements and automation, evaluating the integration and effectiveness of tech systems.	Intelligence [E], Automation [E], Technology [G], Functionality (IT)[G], Intelligent services [H], Intelligent scheduling [H], Technology environment [J], Facilities and equipment [K], Information technology [K], Digital intelligence services [K], Infrastructure [L], Business integration [L]
7	Port management	Focuses on strategic, administrative, and organizational aspects, assessing management strategies and information dissemination.	Management [G], Information [G], Production management [H], Intelligent management [K], Business synergy [L]
8	Risk control and safety	Emphasizes safety, security, and risk management, ensuring maritime safety and operational reliability.	System flexibility [B], Reliability [D], Maritime safety [F], Risk management and control [H], Safety and security [I], Quality and efficiency [L]
9	Human and tangible assets	Pertains to human resources and physical assets, evaluating human capital quality and tangible resources.	Tangibles [D], Empathy [D], Human capital[G]

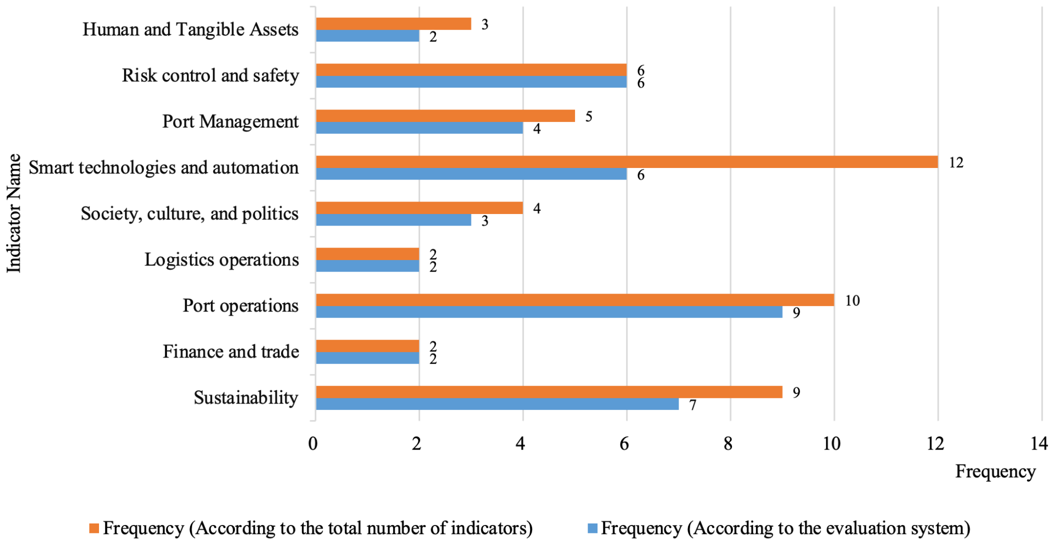

Fig. 1. Frequency statistics of indicators

The first-level indicators of "Smart technologies and automation", "Port operations", and "Sustainability" are the focal points across the literature. "Risk control and safety" and "Port management" also exhibit relatively high frequencies. This finding reflects the emphasis on smart port intelligence, environmental sustainability, and safety. Scholars have constructed evaluation frameworks for smart ports from various perspectives. These frameworks are being continuously refined to assist in evaluating smart port implementation. Although official institutions have provided guidelines for evaluating smart ports, these evaluation standards focus mainly on "smart" aspects related to technology. In some successful cases of smart ports, we have found that the smooth development and operations of smart ports require more than just technology but are influenced by institutional factors, such as cooperation with research institutions and policy support. We explain successful cases in the next section.

3. Understanding smart ports

Following the comprehensive literature review in the previous section, this section will expand our understanding of smart ports by examining the Tianjin Port as a principal case study.

3.1. Defining smart port

The concept of a "smart port" has garnered substantial scholarly attention in port operations. While definitions vary (Othman et al., 2022), a consensus emerges: these ports represent technologically advanced entities designed to enhance operational efficiency, environmental sustainability, and the connectivity fostered through integration and collaboration among various stakeholders. We compile the original sentences from the existing literature on the definition of smart ports in Appendix A.

Several researchers highlight the critical role of technology integration in characterizing smart ports. Rajabi et al. (2018) and Philipp (2020) primarily describe a smart port as one that significantly incorporates the Internet of Things (IoT), thereby creating a network of interconnected devices—such as sensors, RFID tags, automated cranes, and gate systems—that communicate and cooperate to perform complex tasks efficiently. Furthermore, Chen et al. (2019b) and Hsu et al. (2023) extend this technological purview by underscoring the integration of cloud computing, big data, mobile internet, and intelligent sensing technologies. For instance, the Port of Rotterdam, in its ongoing collaboration with IBM, exemplifies the integration of these technologies in developing smart ports. This collaboration includes a comprehensive IoT network to create a digital twin, enhancing operational efficiency and safety. These efforts demonstrate how smart ports leverage connectivity, cloud computing, and IoT to optimize operations and contribute to the global and local economy (Port of Rotterdam (2018). They argue that such a wide-ranging integration enables comprehensive perception, deep computing, and intelligent integration of various port operations.

Automation is another vital component characterizing smart ports, as described in several studies. Rajabi et al. (2018), Philipp (2020), and Hsu et al. (2023) underscore the critical role of automation in shaping smart ports. The studies emphasize the high degree of automation in smart ports, which manifests in different operations such as cargo handling and ship movements.

Operational efficiency forms a significant aspect of the smart port concept, focusing on data-driven decision-making. Triska et al. (2022) emphasize real-time data handling capabilities as central to informed decision-making in smart ports. Boullauazan et al. (2023) and Li et al. (2023) focus on optimizing goods and information flow and leveraging smart-technology-based solutions, such as artificial intelligence, to enhance the efficiency of port users and the workforce. These definitions suggest that smart ports prioritize operational efficiency, benefitting the supply chain.

Several studies have introduced the aspect of environmental sustainability into the smart port discourse. Both Gonzalez et al. (2020) and Heikkilä et al. (2022) assert that environmental sustainability is a key feature of smart ports, highlighting the need for green practices, such as renewable energy use, emission controls, water management, waste reduction, and efficient logistics to reduce environmental impact (Molavi et.al., 2020). Some researchers emphasize the aspect of connectivity and collaboration. Gonzalez et al. (2020) argue that a smart port should integrate with the concept of a Smart City, while Chen et al. (2019b) envision a port that promotes organic connections and resource sharing among various stakeholders within the port ecosystem.

However, the academic discourse often presents a piecemeal view of smart ports, with individual aspects like technology, automation, or sustainability examined in silos. Our study aims to bridge this gap, offering a holistic definition of smart ports that underscores their dynamic nature, which is influenced by cutting-edge technologies, environmental imperatives, and comprehensive connectivity. This "organic and continual evolution" is evident in the ever-evolving partnerships within the port ecosystem, enhancing operational capabilities and fortifying the supply chain.

Based on the relevant discourse in the existing literature and the subsequent section on the investigation of smart port cases, we propose the following definition of the smart port, which will be further explored in the subsequent part of this section through our case analysis.

A smart port represents the organic integration of next-generation technologies (such as artificial intelligence, IoT, big data, etc.), with port operations, forming a continually evolving ecosystem of multiple participants (such *as port companies, maritime authorities, transport institutions, etc.). By applying advanced technology and data-driven entities, this ecosystem enables efficient port operations, promotes environmental sustainability, and seamlessly integrates with broader city infrastructures and supply chains. Simultaneously, smart ports use their robust data analysis capabilities to support decision-making, enhance safety, and effectively manage risk.*

Within this framework, we can distinguish smart ports from automated terminals and green ports. Automated terminals, while crucial to smart ports, focus on enhancing efficiency and safety in ship operations, cargo handling, and yard management through automation in loading, unloading, movement, and stacking. This automation aims at maximizing operational efficiency rather than realizing intelligence. However, as demonstrated by the progress made in fully automated ports such as Shenzhen, Hamburg, and Los Angeles (detailed in Appendix C), there is still room for improvement in integrating and optimizing various port operations. On the other hand, smart ports embody a broader ecosystem, aiming not only at operational optimization—a core goal of automated terminals—but also at integrating and synergizing various port operations. For example, smart ports can optimize intermodal operations, reduce congestion, and improve overall supply chain efficiency by integrating with city infrastructure and transportation networks. Additionally, smart ports can collaborate with shipping lines, logistics providers, and other stakeholders to develop innovative solutions that benefit the entire port ecosystem, such as blockchain-based cargo tracking systems and shared data platforms for enhanced visibility and decision-making. Green ports represent a noteworthy embodiment of smart ports, with green development being one of the primary objectives of a smart port.

3.2. Ecological perspectives on smart ports

The establishment and development of smart ports can be elucidated through the lens of an ecosystem. To begin with, we will outline the application of the ecosystem perspective in the realm of management studies.

The ecosystem perspective is currently used in a wide range of research in the business domain. Tansley (1935) first introduced the concept of ecosystem, in which he tried to study the relationship between organisms and their natural environment from a systems perspective, defining an ecosystem as "*a community or collection of organisms or their associated physical environment at a particular site*". Later, not only have researchers studied ecosystems in the field of natural sciences, but some scholars of management research have drawn on this concept to analyze management phenomena in enterprises (Hazenberg et al., 2016), industries (Korhonen, 2001), regions (Hillebrand et al., 2008), and countries (Hult et al., 2020).

In business, Moore (1996) introduced the revolutionary concept of business ecosystems, which fundamentally altered our understanding of business interactions and strategies. He depicted these ecosystems as dynamic networks of organizations and interest groups that support each other and co-evolve within a shared environment. This concept shifted the focus from individual businesses to the broader network they inhabit and underscored the importance of adaptability and collaboration for business success. Since then, various researchers have proposed concepts such as corporate ecosystems (Hanson et al., 2012), industrial ecosystems (Ashton, 2009), and innovation ecosystems (Oh et al., 2016) and have drawn on ecological concepts to study the application of ecological niches (Santana et al., 2008), evolution (Demil and Lecocq, 2010) in business. This development reflects a paradigm shift in research, and these studies have contributed to the understanding of industry, innovation, and synergy. Although researchers have defined these concepts differently, there are similarities in their studies in that they all shift from an elemental to a systemic view, emphasizing the symbiotic organization-environment relationship.

There is extensive literature on the evolution of the port as an organization (Baltazar and Brooks, 2006; De Martino and Morvillo, 2008; Ircha, 2001), and port development is considered to be the result of a multifaceted synergy, providing a basis for applying the population ecology theory to port research. The economic circle formed by the port as a platform and core also significantly fits the characteristics of an ecosystem, and relevant studies have been carried out on port enterprise industrial ecosystems or port industrial ecosystems. For instance, Golzarjannat et al. (2021) proposed a port business model configuration. Kapkaeva et al. (2021) constructed a port IT ecosystem using the port of Hamburg as an example. Botti et al. (2017) used service science theory to redefine the port supply chain as an intelligent service system. These studies explain ports using the ecological perspective. However, despite these notable instances of applying the ecosystem perspective to port studies, its comprehensive adoption in logistics and shipping remains relatively limited. These limitations are mainly manifested in the following aspects: 1) the number of studies in shipping and logistics is relatively small compared to those on the business side; 2) while scholars have studied different port and shipping scenarios, as the industry is constantly evolving and presenting new application scenarios, there are still many areas that need to be further explored. Our study on smart ports is a typical example, as the components, evolution, and relationships involved in smart ports are very different from the scenarios examined in previous studies. As the shipping and logistics industry continues to evolve and new models such as smart ports emerge, the application of the ecosystem perspective in this field is expected to deepen, highlighting the ample room for future studies to contribute to the development of the industry.

By applying the ecosystem perspective to smart port research, we can understand the dynamic interactions within and outside the smart port as well as the interdependencies between different components, providing a more comprehensive and systematic approach to analyzing and understanding smart ports, thus providing a more scientific and sustainable path and strategy for their planning, design, operations, and management. We compare natural ecosystems with smart ports: components, interspecific relationships, evolution, structure, and flow (see Table 3). Based on the current developmental stage of smart ports, where the application of various technologies has yet to mature, this paper focuses on two aspects: the development and operations of smart ports.

Table 3. Natural ecosystems and smart ports

	Natural Ecosystems	Smart Ports
Components	Producers, consumers, decomposers, abiotic components	Multiple components include governments, shippers, technology companies, and financial institutions.
Interspecific Relationships	Ecological relationships, such as parasitism, symbiosis, predation	Symbiotic relationships, cooperation
Evolution	Emerging, Growth, Maturation, Extinction	From simple to complex
Flow	Matter flow, energy flow, information transfer	Information flow, goods flow.

The ecosystem view of the smart port is analogous to that of a natural ecosystem, emphasizing the complexity, dynamism, and interconnectedness, intrinsic to both systems. Like a natural ecosystem comprising producers, consumers, decomposers, and abiotic components, a smart port ecosystem encompasses a variety of stakeholders, including governments, shippers, technology companies, and financial institutions, all playing crucial roles. The relationships among these components vary; while natural ecosystems may exhibit parasitism, symbiosis, and predation, smart ports primarily foster symbiotic relationships and stakeholder cooperation. Evolution is another shared characteristic; both ecosystems transition from simpler to more complex structures—natural ecosystems through stages of emergence, growth, maturation, and potential extinction, and smart port ecosystems adapt to demands and technological advancements. Smart ports initially facilitate basic ship loading and unloading with automation and evolve to meet expanding stakeholder demands. This evolution is evident in smart ports adopting technologies like blockchain for efficient goods regulation by customs and governments, enhancing payment processes through financial collaborations, and streamlining cargo pick-up with paperless processes. Lastly, both systems rely on efficient and effective flow management: matter, energy, and information transfer in natural ecosystems, as well as information and goods flow in smart ports. For example, the interaction between stowage and yard planners within a smart port illustrates the operational dynamics of these ecosystems. IoT devices enable real-time 5G communication between dock cranes, Automated Guided Vehicles (AGVs), and yard cranes, optimizing container handling to speed up goods movement and information flow. Recognizing these parallels facilitates understanding smart ports as ecosystems, underlining the importance of component interaction, dependencies, and resource flow management, ultimately leading to more efficient, resilient, and sustainable smart ports.

The Tianjin Smart Port is a pertinent example of enhancing comprehension in this study. This port was selected as the primary case for analysis for several compelling reasons.

1) As a pioneer in smart port development, Tianjin provides a wealth of case studies for understanding and promoting the theory and practice of smart ports. The development of smart ports relies heavily on advanced 5G technology, and China, which has a leading role in this area (Min, 2022), has accelerated the rapid growth of smart ports. Among the smart ports in China, the C-section smart container terminal of the port is the first globally to achieve “smart carbon-zero” (National Development and Reform Commission of PRC, 2021; Safety4sea, 2021). Its unique, intelligent green energy system enhances the efficiency of port operations and aligns with the philosophy of green shipping. The numerous innovative achievements of Tianjin, including the intelligent horizontal transportation management system based on artificial intelligence and the commercialization of the in-port ultra-L4 autonomous driving collaboration (Ministry of Transport of the PRC, 2023; AP News, 2023), offer significant references for the development of smart ports in China and globally.

2) Regarding smart port development, Tianjin demonstrates significant efficiency and effectiveness. The smart port was completed and officially operated in just 21 months (Central People's Government of the PRC, 2021; Maritime Gateway, 2021). This comprehensive completion encompassed not only the terminal infrastructure, including berths and fairways, but also the introduction of several innovative features such as an intelligent horizontal transportation system, smart horizontal transport robots, a high-precision environment enabled by Beidou

satellite base stations and 5G technology, and a zero-carbon energy system powered entirely by renewable sources, setting a new standard for port intelligence and low-carbon development globally. In 2022, the average operational efficiency of the second container terminal of the port reached 36 standard containers per hour, the average running efficiency of the single bridge crane increased by 20%, and the comprehensive energy consumption of a single container decreased by 20%. These figures are at the forefront of smart ports worldwide (Xinhuanet, 2023) - this exceptional efficiency and operational performance contrast sharply with other smart ports. For instance, the Ma Wan Smart Port in Shenzhen took considerably longer to achieve full automation and intelligence in their port solutions, from launching the iRC system[3] in 2014 to completing the CMPort-CTOS V4.5[4] in 2020. Likewise, despite being an international shipping center, Hong Kong has not yet finished its transition to a smart port. Meanwhile, Singapore has only recently proposed a smart port development plan and is expected to complete the project by 2023. Thus, in comparing the development time, operational efficiency, and smart-level advancements, Tianjin's achievements underscore its suitability as the main case study in the analysis of smart ports.

3) Tianjin Port is one of the most comprehensive data-disclosing smart ports globally, and its detailed publicity materials provided abundant sources for our case study. Tianjin Port Group's WeChat public account has over six hundred original contents. The clear stage characteristics of its development process offer a valuable reference for the smart transformation of other ports. Moreover, Tianjin has achieved a series of breakthroughs in cooperating with other entities, providing a significant practical perspective for understanding the development process of smart ports and the challenges they may encounter.

The materials selected for this study include policy papers on smart ports, industry research, company annual reports, and company social responsibility reports. In addition, we also retrieved media reports on smart ports and information disclosed by companies on their initiative and screened events related to the topic of this study as supplementary materials. Moreover, this study also interviewed smart port builders and researchers to understand smart ports better.

This section provides a new understanding of smart ports from four perspectives: Components, Relationships, Evolution, and Flow.

3.2.1. Components

Regarding components, there are more similarities between natural ecosystems and smart ports. Table 4 compares components and their connotation between natural ecosystems and smart ports.

[3] The iRC system is an intelligent remote control technology developed by China Merchants Port

[4] It refers to a specific version of a Container Terminal Operating System developed by China Merchants Port (CMPort).

Table 4. Natural ecosystems and smart port roles

Component	Natural Ecosystem Connotation	Component	Smart Port Connotation
Producers	Fundamental entities that convert solar energy into chemical energy accelerate the material cycle.	Builder	Refers to the subject directly involved in the development of the port (e.g., port companies, technology companies)
Consumers	Organisms that process and reproduce primary production regulate biological populations.	Consumers	Refers to utilizing and benefiting from the smart port's services, driving its primary activities. (e.g., shipping companies, trading companies, and logistics companies)
Decomposer	Entities that break down organic matter, recycle nutrients, and ensure ecosystem sustainability.	Supporter	Refers to the subject that supports and promotes smart ports, ensuring their sustainability and growth (e.g., government and transportation institutions)
Non-biological components	Elements that provide the necessary living environment and nutrients for biological components.	Environment	Refers to the natural environment (e.g., sustainability) and the man-made environment (e.g., policy environment, human talent)

We have constructed a model of smart port participants by analyzing the roles, responsibilities, and interactions of various stakeholders involved in the development and operation of smart ports, as shown in Fig. 2.

1) Builders: The builders of smart ports include port companies, technology and commerce companies (e.g., banks, trading companies, e-commerce companies, etc.), and construction companies (e.g., engineering companies involved in the actual construction of ports, such as CCCC Fourth Shipping Engineering Bureau Co., Ltd., who built the Ma Wan Smart Port). They play a crucial role in the smart port ecosystem, serving as the foundation and driving force of the entire system. They are responsible for port construction, operations, and management and provide technical support and services to smart ports.

Port companies are the main body of smart port development, management, and operations. For example, the Tianjin Port Group has been the core organizer, promoting project implementation during the development of smart ports. Technology companies are responsible for the development and implementation of advanced technologies of smart ports, promoting technological innovation and service upgrades. In developing the Tianjin smart port, Huawei collaborated with Tianjin Port Group to create multiple industry-leading 5G application scenarios, which were shortlisted for China's first batch of new infrastructure construction projects. They also successfully developed the world's first intelligent horizontal transportation system based on 5G+AI. Commerce companies primarily serve the financial needs of smart ports and integrate various financial resources. For instance, the Bank of China provides Tianjin Port Group with one-stop comprehensive financial services, including supply chain finance, financial insurance, and special financial products, to meet the financial needs of the port. Construction companies are responsible for constructing smart ports, including infrastructure, equipment installation, and commissioning. They ensure smooth construction through their professional skills and experience.

2) Consumers: Smart port consumers are enterprises and individuals participating in, using, and benefiting from the intelligent services of port providers during development and operations. They are critical in driving

technological advancements, service innovation, and business expansion in the smart port ecosystem. The smart port consumer group comprises shipping companies, logistics service providers, import/ export trading firms, and other businesses related to port operations. Using Tianjin Port as an example, smart port consumers have played a pivotal role in the development of the port. In June 2020, Tianjin Port and Haifeng International Holdings Co., Ltd. collaborated to optimize shipping route networks (e.g., increase port calls in Tianjin port, open new routes, etc.), expand container services, and promote the development of sea-rail combined transportation. Furthermore, Tianjin Port and China COSCO Shipping Group, Xiamen Port Holding Group, and Zhonggu Logistics signed a strategic cooperation agreement to enhance domestic container shipping routes between Tianjin Port and Xiamen Port, increase route density, and promote regional economic complementarity. These examples highlight the importance of smart port consumers in driving technological advancements, service innovation, and business expansion. Their collaboration with ports promotes sustainable development, enables complementarity, and yields mutual benefits, ultimately enhancing the efficiency, reliability, and ease of use of shipping and trade services.

3) Supporters: In natural ecosystems, decomposers play a pivotal role in breaking down organic matter, recycling nutrients, and ensuring the sustainability of the ecosystem. Similarly, in the smart port ecosystem, supporters, such as government agencies, quality assurance institutions, and transportation departments, ensure the sustainability and growth of the port. They provide essential services and support for developing and operating ports without directly profiting from them. The government is the core supporter of smart ports and is responsible for regulating port operations and formulating policies and regulations. For instance, the Tianjin government has set the goal of building a world-class smart and green port to advance the development of the Tianjin Northern International Shipping Hub. In parallel, the national government has issued guidelines to accelerate the hub's development, guiding the development of the port's core areas. Quality assurance agencies are responsible for inspecting, monitoring, and maintaining port facilities and equipment to ensure they comply with relevant standards and regulations. For example, Tianjin Port Bin Technology Development Co., Ltd. provides precise testing data and high-quality services for engineering projects to ensure their quality.

Transportation institutions, such as airport and railway port groups, provide logistics services and transportation support, enabling goods to be transported quickly and safely within the port and facilitating efficient transportation methods such as port-hinterland and port-railway connections. For instance, by integrating smart sensors, RFID tags, and blockchain technology, smart ports can enable seamless tracking and management of cargo across different modes of transportation, improving visibility, security, and efficiency compared to traditional port-hinterland and port-railway connections. These collaborations have likewise boosted the city's development. For example, Tianjin Port Group and Tianjin Binhai Airport have signed a strategic cooperation agreement to jointly leverage the advantages of sea-air port functions, promote the formation of linkage development effects, promote the creation of a new development pattern, and serve the development of Tianjin's "twin cities" and "dual centers"[5].

Research institutions, such as design and research institutes, universities, and design institutes, provide research and development support for ports, studying new technologies and processes to help ports improve productivity and

[5] Tianjin's "twin cities" refer to the collaborative development of Tianjin's urban center and its port area, while "dual centers" refer to the establishment of Tianjin as both an international consumption center and a regional trade and business center.

innovation capabilities. For example, Tianjin Port Group has formed a strategic alliance with Tianjin University of Science and Technology, Shanghai Maritime University, and other research institutes and universities to create a long-term stable multi-disciplinary cooperation mechanism, overcoming a series of world-class difficulties in smart port development. Financial institutions, such as banks and investment companies, provide funding and financing support to help ports expand their businesses and improve their facilities. Maritime authorities manage and supervise ships and maritime activities in ports to ensure safe and smooth operations. For example, Tianjin Maritime Bureau maintains close communication with Tianjin Port Group, launching "eight measures"[6] to assist in developing Tianjin Port, improving service capabilities and operational efficiency, and reducing operating costs.

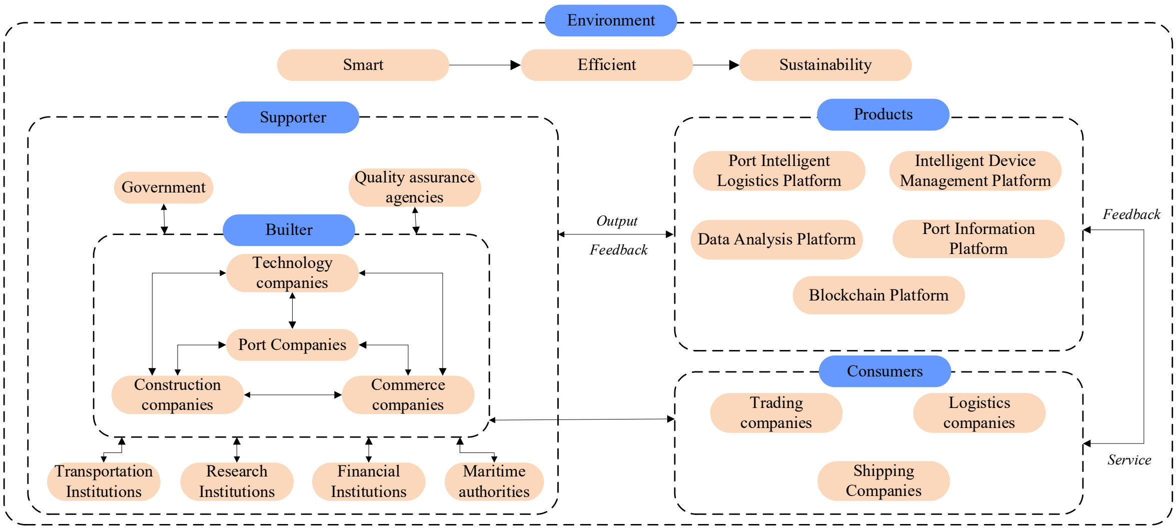

Fig. 2. Smart port model

3.2.2. Relationships

Synergy and cooperation among various stakeholders have emerged as vital components for achieving mutually beneficial and win-win outcomes (Chen and Chen, 2007). By supporting and complementing each other's strengths during collaborative efforts while facing challenges, all participants enhance their competitiveness and contribute to societal prosperity (Hult et al., 2020). This notion is particularly evident in the development and operation of smart ports. Throughout the different stages of smart port development, few accomplishments are solely achieved by a single entity; instead, they typically involve the collaboration of two or more distinct categories of stakeholders. For instance, Tianjin Port's intelligent horizontal transportation system is a joint effort between the Tianjin Port Group, Huawei, China Mobile, and other companies. This partnership leverages Huawei's technical advantages in areas such as autonomous driving, cloud computing, and the Internet of Things, as well as China Mobile's expertise in communication technology. In developing smart ports, the need for synergies and cooperation is critical: Collaborative efforts of different stakeholders, contributing their unique expertise, promotes the rapid and efficient development of smart ports. The significance of cooperation becomes particularly apparent, and its

[6] The 'eight measures' introduced by the Tianjin Maritime Bureau are a set of strategic initiatives designed to support the transformation and upgrade of Tianjin Port. These measures focus on increasing efficiency, pollution prevention, search and rescue operations, and the integration and sharing of data, etc.

advantages are more pronounced in smart port scenarios that face technical challenges, seek operational benefits, or strive for sustainability objectives. As a complex system involving the collaboration of multiple parties, the interdependence between different types of participating subjects in smart port activities is equally prevalent. This dependency manifests itself in the following three aspects:

Firstly, the high complexity of smart port technology applications necessitates the collaborative involvement of various stakeholders in creative activities (Yau et al., 2020). Secondly, in the operation of a smart port, a single stakeholder relies on the coordination and cooperation of the preceding and subsequent links in the task chain and the synchronized innovation of the upstream and downstream partners in the industry chain (Walters et al., 2007). The operational links of a smart port are closely connected, and various stakeholders need to coordinate and collaborate to establish an integrated task chain and industry chain that ensure efficient operations. Thirdly, the development and operation of a smart port involve the influence and supervision of numerous parties.

3.2.3. Evolution

Over time, organizational development stages have been extensively studied, including creation, growth, transformation, decline, and eventual cessation (Hannan and Freeman, 1977). Port development is not an overnight process, and ports have undergone four stages of transformation, reflecting the continuous enrichment of their business models. In particular, smart ports employ artificial intelligence, big data technologies, and other tools to support efficient and sustainable development, necessitating a phased approach. In April 2018, the world's first unmanned electric truck began trial operations at Tianjin Port. The truck has a BeiDou positioning system, laser radar, millimeter-wave radar, cameras, and various AI technologies such as deep perception and intelligent scheduling. The data generated by these unmanned electric trucks is integrated with the port's high-speed information network, IoT platform, and spatial visualization information system, forming an interconnected data network. This approach facilitates rapid intelligent loading and unloading of container ships and enables dynamic and scientific allocation of various port machinery within the area. Triska et al. (2022) divided smart port development into five maturity stages: pre-smart, initial, intermediate, advanced, and cutting-edge, characterizing each stage about enablers, applications, and outcomes. Similarly, Boullauazan et al. (2023) classified smart port maturity into five capability levels, from optimization to knowledge creation. However, most of these maturity models adopt a technical perspective and overlook the involvement of multiple stakeholders, such as port companies, shipping companies, government, etc.

Tianjin Port's smart port development history demonstrates continuous improvements in intelligence and green initiatives and a gradual expansion of business scope, laying the foundation for building a green and smart port. The port’s development can be divided into three stages, separated by two significant events. The first event occurred on December 28, 2019, with the construction of a new generation of smart container terminals, marking the beginning of the second stage. The second event occurred on October 17, 2021, with the operations of the world's first “smart carbon-zero” terminal at Tianjin Port, marking the third stage's start.

During the exploration period, the port established an “Academician Workstation”, a dedicated research and development platform designed to gather the wisdom and experience of academicians from the Chinese Academy of Sciences or Chinese Academy of Engineering, promoting scientific and technological innovation and progress.

In this phase, the port focused on technology research and development strengthened connections with academia and industry, and promoted intelligent and green development. As intelligence levels improved, Tianjin Port pursued greener operations. In the growth period, the port increased investment in green intelligent technology and equipment, such as distributed photovoltaic power generation systems and unmanned electric trucks, enhancing operational efficiency and environmental friendliness. Concurrently, the port emphasized collaboration with various entities, such as governments, enterprises, and research institutions, to jointly advance green and smart port development. Upon entering the mature development period, Tianjin Port's intelligent and green development ecosystem gradually matured, and the smart port framework became better defined, with a consistently expanding business scope. The port improved its intelligence and green development levels in this stage by adopting advanced technology and management methods. These achievements include a smart green energy system that combines wind and solar power to create a self-sufficient, zero-carbon terminal, the world's largest fleet of clean energy level transport vehicles, and a green smart energy demonstration project. Additionally, Tianjin Port introduced a series of innovative applications, such as the world's first fully IoT-enabled container terminal and the first batch of AI trainers in China's port industry, injecting new vitality into the port's sustainable development.

We have organized the key events of the Tianjin Smart Port, as shown in Fig. 3. To better understand the collective evolution of Tianjin Smart Port, we extracted the partner information disclosed by Tianjin Smart Port and used Gephi to illustrate it, as shown in Fig. 4. The information for this illustration was obtained from Tianjin Port's annual report, media reports, and data disclosed by Tianjin Port's WeChat public website. In this illustration, different colors represent different types of entities, corresponding to the classifications in Fig. 2. Fig. 4 shows that the entities collaborating with Tianjin Port have steadily increased as the smart port developed. Particularly noteworthy is the transition from initially collaborating with a limited range of entities, such as technology companies, construction companies, trading companies, logistics companies, and commerce companies, to collaborating with entities of all kinds throughout the exploratory phase to the growth phase.

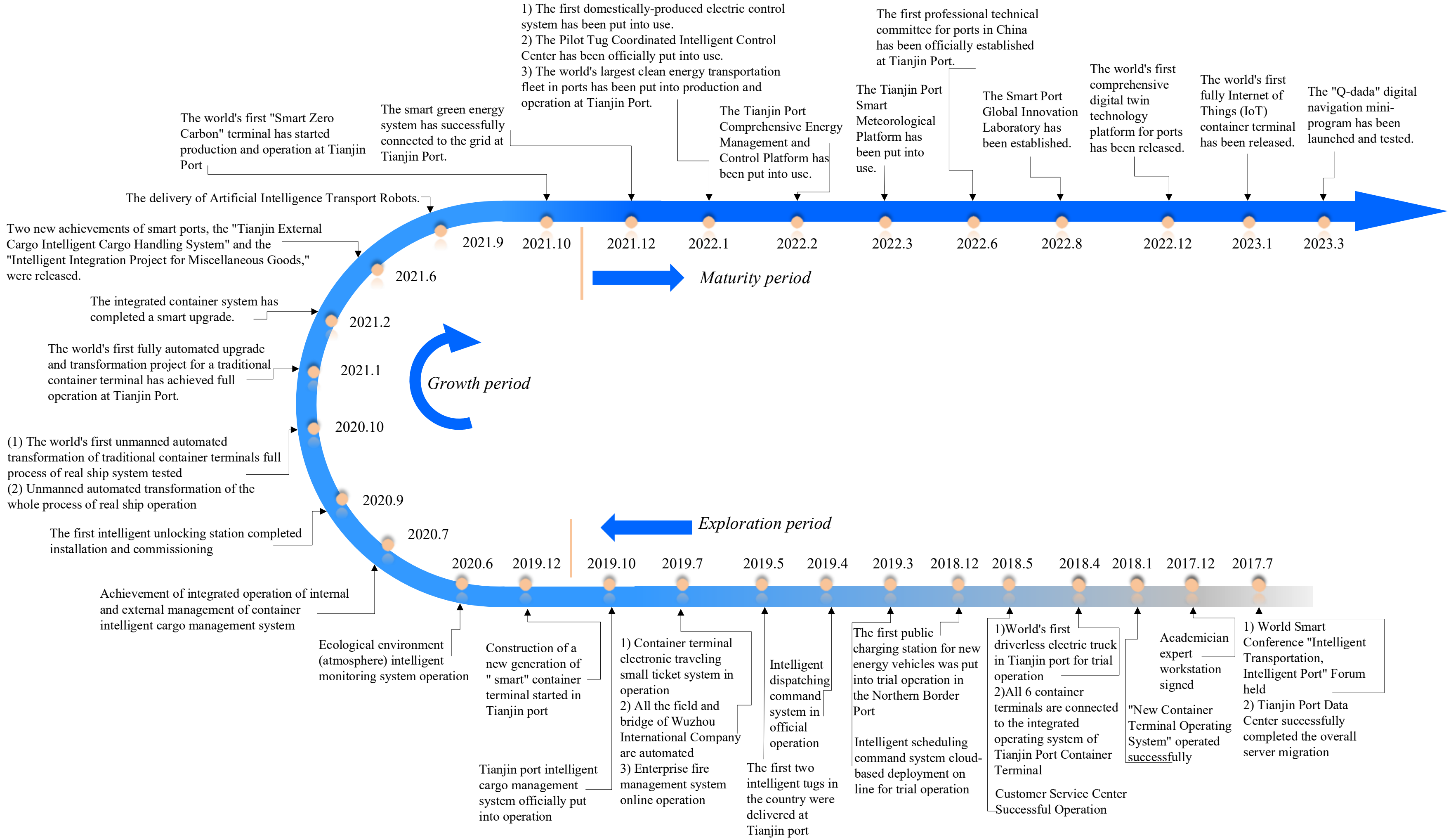

Fig. 3. Key events in developing Tianjin Smart Port

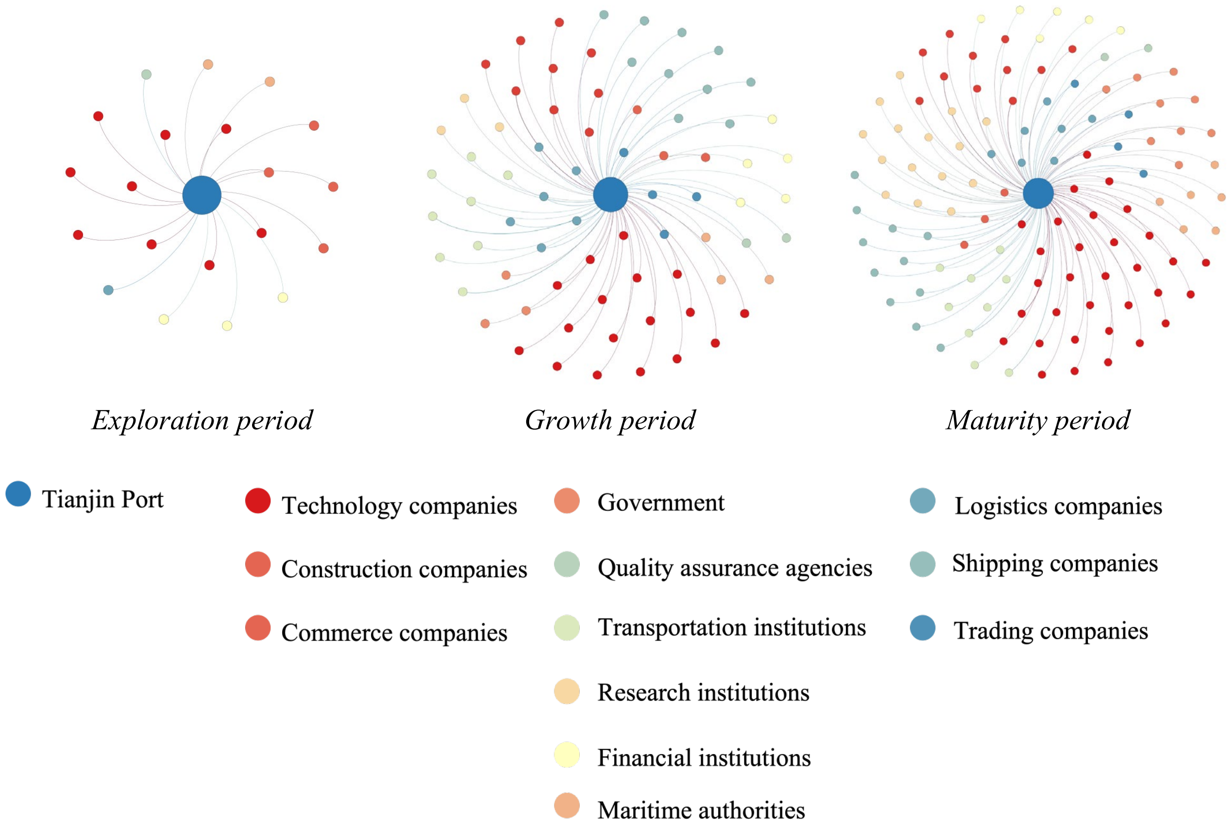

Fig. 4. Tianjin smart port partners and their evolution

3.2.4. Flow

Material and energy flows are foundational characteristics of natural ecosystems (Sharma and PD, 2012). In these ecosystems, materials flow pertains to transforming elements constituting living organisms and all non-living entities' essential substances. Energy flow delineates the unidirectional and progressively diminishing movement of energy within the ecosystem. These concepts can be likened to logistics and information flow in the context of smart ports.

Logistics flows in smart ports primarily refer to transporting and storing goods, including loading/unloading, stacking, picking, and packaging. High efficiency in logistics flows is one of the hallmarks of smart ports. By harnessing technologies like the Internet of Things (IoT) and artificial intelligence, smart ports ensure intelligent cargo management, swift transshipment, efficient distribution, and expedited customs clearance, elevating logistics efficiency. For instance, on January 17, 2023, Tianjin Port launched the world's first fully IoT-enabled container terminal, which achieves full connectivity among the six key elements of people, vehicles, containers, ships, cranes, and yards. By applying digital twins, video AI, and intelligent sensing technologies, the terminal enables comprehensive IoT, digitalization, and intelligent solutions across various scenarios, including production operations, safety management, energy conservation and environmental protection, and smart buildings. Compared to other automated container terminals currently operating worldwide, this terminal boasts multiple overlapping advantages, including a wider range of IoT applications, more application scenarios, better integration effects, and stronger sustainability.

Information flow in smart ports concerns the continuous and dynamic movement, exchange, and data processing. It is not just about the presence of data but how it circulates, gets updated, and influences decisions in real-time. This flow includes real-time data sourced from port facilities and logistics services and data processing via IoT, big data, and cloud computing. This data is disseminated, shared, and acted upon fluidly, offering real-time decision-making support and service enhancements for stakeholders such as logistics providers, cargo owners, and freight forwarders. Such a flow fosters a collaborative environment, optimizing information exchange and interactions throughout the logistics chain, ensuring that data is always current, relevant, and actionable.

Taking Tianjin Port as an illustrative example again, the Tianjin Port Group has collaborated with customs to devise an intelligent control system to bolster the oversight of domestic and international trade goods. This system boasts over 500 intelligent cameras that use computer vision and AI algorithms to detect, recognize, and analyze objects or events in their field of view. These cameras are stationed at key locations like berths and yards, enabling precise container identification, thereby streamlining regulatory processes. Another innovation at Tianjin Port is the Smart Stocking System, a comprehensive intelligent operation system integrating multiple functions, including tally, business processing, customer service, fee settlement, and enterprise management. Compared to traditional methods, this system significantly reduces manual operations, decreasing personnel workload and shortening manual operation times by over 87%. It also incorporates electronic ship maps, improving product delivery and enhancing customer service. Furthermore, Tianjin Port has implemented a Smart Gate System that automatically identifies and validates trucks, containers, and cargo, reducing gate processing times and enhancing security.

3.3. The concept of the health of smart ports

Developing smart ports is subject to challenges and constraints. Substantial investment requirements, lengthy development periods, and coordination of multiple elements can slow progress. Limitations also exist in technological reserves (the pool of existing technological knowledge and innovations), capital accumulation, innovation capabilities, and human resources. Therefore, developing smart ports is considered a long-term, gradual, and continuous process. A healthy smart port usually facilitates more efficient advancement in its development. By fully leveraging advantages in technological reserves, capital accumulation, innovation capabilities, and human resources, smart ports can achieve development goals in a shorter period. Doing so implies that, at the initial stages of smart port development, strategic planning, adequate investment and resource allocation, and an emphasis on innovation and talent development are necessary for the rapid development of smart ports.

The study of ecosystem health can be divided into three stages according to the contributions to the academic development of ecology. After Tansley (1935) proposed the concept of ecosystem, Leopold (1941) introduced the concept of land health and established a system of indicators of land dysfunction. Rapport et al. (1998) introduced the concept of ecosystem health, arguing that healthy ecosystems are stable and sustainable and maintain their organization and autonomy over time. After this, studies were conducted to evaluate the health of ecosystems over time, and various scholars analyzed a system's health status through different evaluation methods. den Hartigh et al.

(2006) introduced the concept of health in the ecosystem to the business ecosystem and developed measurement tools that can detect the financial and network status of individual partners and help improve the performance of the business ecosystem.

More studies and more mature methods have been used to analyze the health of natural ecosystems. One of the more influential models for evaluating health in academia is the VOR model proposed by Costanza (1992). The model uses vigor, organization, and resilience to characterize ecosystem health. In assessing the health of smart ports, we can use analogy and reference (Kraus, 2015) to establish the evaluation framework for smart port health.

The health of smart ports can be described as a dynamic and adaptive system, achieving a harmonious equilibrium among various components such as infrastructure, technology, operations, and ecological factors. This balance ensures efficient and safe port operations, minimizing environmental impact and maximizing stakeholder benefits. A healthy smart port demonstrates adaptability and resilience in response to evolving conditions, including economic fluctuations, technological advances, or environmental changes. Moreover, it fosters effective communication and collaboration among stakeholders, facilitating proactive decision-making and adopting innovative solutions to address emerging challenges. A healthy smart port promotes sustainable growth by prioritizing energy efficiency, waste reduction, and resource optimization. By incorporating advanced technologies and practices, smart ports enhance operational efficiency, decrease emissions, and mitigate environmental risks, thus aligning with broader sustainable development and climate change mitigation objectives. The health of smart ports embodies a comprehensive and multifaceted concept, emphasizing the harmonious synergy among technological, operational, ecological, and social dimensions. A healthy smart port contributes to the success of the shipping industry and its stakeholders by pursuing efficiency, resilience, sustainability, and inclusivity.

4. Developing the health of smart ports evaluation framework

This study's research process and methods are shown in Fig. 5. This section constructs the evaluation framework of the health of smart ports and calculates each indicator's weight.

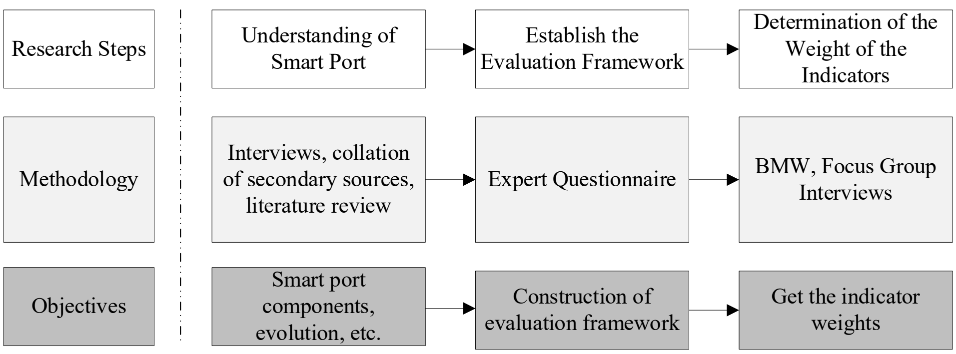

Fig. 5. Research process

4.1. Evaluation framework establishment

The smart port ecosystem, involving the evaluation of multiple aspects, necessitates a multi-level and multi-objective decision-making process to select an evaluation framework. The selection of evaluation items must adequately consider the relationships between the elements within their context and the smart port ecosystem. The following principles should be adhered to: systematic (Jeon et al., 2016), operability (Bottero, 2011), and scientific (Chen et al., 2019b).

The ecosystem health evaluation provides useful theoretical guidance to construct an evaluation framework for smart ports. Costanza (1992) proposed the VOR (Vigor, Organization, and Resilience) model evaluation framework, which encompasses the main aspects of the ecosystem and involves various disciplinary fields such as ecology, economics, and biology. However, although the VOR model represents a crucial guideline, refinements are necessary during the implementation process. We initially propose four evaluation dimensions for smart ports: Vitality, Coordination, Growing, and Development. These draw on the VOR model, addressing the shortcomings of existing studies while considering the inherent characteristics of smart ports.

Our approach to constructing the evaluation framework is depicted in Fig. 6. Development (D) represents the external support for constructing a smart port, while Growing (G) refers to the potential of the smart port itself. The Development (D) and Growing (G) indices assess the future dimension of the smart port, demonstrating its development prospects. The Vitality (V) and Coordination (C) indices represent the current dimension, showing the evaluation of the smart port's development achievements. Vitality (V) represents the comprehensive ability demonstrated in pursuing efficiency and intelligence, while Coordination (C) refers to the coordination ability between the smart port and the environment. The Vitality (V) indicators utilized in this study follow an approach of assessing the outcomes after the smart port has been developed and put into operation. This method is precise in reflecting the actual effects of smart port applications, compared to solely evaluating the degree of smart port development or focusing exclusively on the level of smart technology application. Consequently, this approach can offer a more extensive and accurate evaluation of smart port development levels, emphasize the importance of actual outcomes, facilitate the identification of issues in smart port application implementation, and provide practical guidance for further improvements. Since most of the smart ports at this stage are container ports, the evaluation framework constructed in this paper considers container ports as the main scenario.

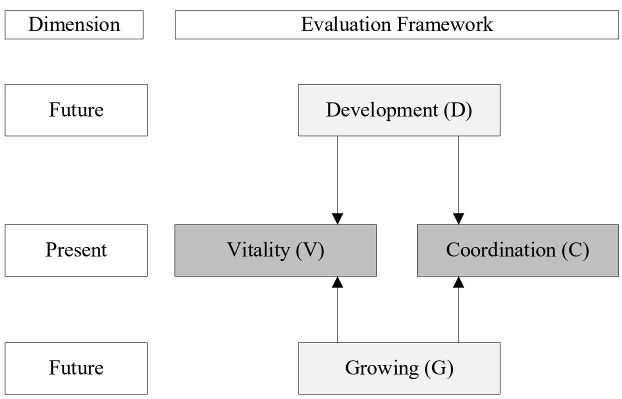

Fig. 6. Construction for the evaluation framework

An expert questionnaire survey was structured around the three main components of smart ports presented earlier. We selected 12 respondents from the pool of experts accessible to our research team, intending to encompass a spectrum of perspectives from different sectors of the Smart Port ecosystem. As evidenced by Boddy (2016), this sample size offers saturation in qualitative data, balancing manageability and diversity.

The chosen experts possessed deep knowledge and experience with smart ports, including their development, operations, research, and usage. Experts were selected based on their recognized field contributions and geographic diversity. Specifically, our experts were selected from Mainland China, Hong Kong (SAR), and Singapore. While these regions are in close geographic proximity and share certain economic and maritime characteristics, they also offer distinct perspectives due to their unique administrative, economic, and infrastructural contexts. Hence, we believe their insights provide valuable perspectives to this research. Information on experts can be found in Table 5.

Table 5. Experts' information

Basic Information	Description	Number of people	Percentage
Gender	Male	7	58.33%
	Female	5	41.67%
	Total	12	100.00%
Age	21-30	4	33.33%
	31-40	4	33.33%
	41-50	3	25.00%
	51-60	1	8.33%
	Total	12	100.00%
Education	Bachelor	5	41.67%
	Master	3	25.00%
	PhD	4	33.33%
	Total	12	100.00%
Professional	Consumers	3	25.00%
	Supporter	5	41.67%
	Builder	4	33.33%
	Total	12	100.00%
Region	Mainland China	8	66.67%
	Hong Kong (SAR)	2	16.67%
	Singapore	2	16.67%
	Total	12	100.00%

We conducted two rounds of data collection, and 12 questionnaires were distributed in each round. We considered all responses valid, and no questionnaire was disregarded as incomplete. The questionnaire appears in Appendix D. No weight calculation was included in the survey at this stage.

The questionnaire in the first round was comprised of two parts. The first part involved information on experts, primarily inquiring about their positions and relationship with smart ports. While we generally understand that the selected experts were associated with smart ports, this part of the questionnaire aimed to gather more detailed information about their roles and expertise. The second part sought their opinion on our evaluation framework. Expert feedback indicated excessive dimensions in the initial evaluation framework, with some being non-operational. We adopted a criterion-based filtering approach: indicators misaligned with our primary objectives or lacking operational relevance were re-evaluated. Overlapping or redundant indicators were consolidated for clarity.

Following these changes, the revised evaluation framework underwent another round of reviews by the same experts, ensuring iterative validation. Based on the results, the experts agreed on the evaluation framework, consisting of four first-level indicators with three second-level indicators under each first-level indicator for 12 second-level indicators. The evaluation framework shown in Table 6 was obtained.

Table 6. Evaluation framework for the health of smart ports

First-level indicators	Second-level indicators	Calculation method	Positive (+)/ Negative (-)	References
Vitality (V)	Efficiency Operations Level (V1)	Average time in port for a single container	-	Ducruet et al., (2014)
	Safety Operation Level (V2)	The number of accidents caused by human factors in the specified time (month)	-	Corrigan et al., (2019)
	Uncrewed Level (V3)	The average number of unit personnel who can operate the equipment at the same time.	-	Jun et al. (2018), Yang et al. (2018)
Coordination (C)	Energy Saving Level (C1)	Average energy consumption of single container operation: (energy consumption of shore bridge operation + energy consumption of yard + energy consumption of horizontal transportation)/total number of containers	-	Chen et al. (2019a), Alaa Othman et al. (2022)
	Emission Reduction Level (C2)	Total gas pollutant emissions	-	Molavi et al. (2020), Alaa Othman et al. (2022)
	New Energy Application Level (C3)	Percentage of new energy equipment: Number of new energy equipment/total equipment	+	Makkawan and Muangpan, (2021)
Development (D)	Financing Support (D1)	Number of investment and financing	+	Campisi et al. (2022), Chuah, (2023)
	Policy Environment (D2)	Number of regional smart port-related policies divided by the total number of policies	+	Karaś (2020), Li et al. (2023)
	Cooperation Capability (D3)	The number of collaborations with research institutes, universities, and technology companies.	+	Douaioui et al. 2018)
Growing (G)	Talent Level (G1)	The proportion of bachelor's degree (and above) to the total number of workers	+	Wei and Wang (2020)
	R&D Level (G2)	Number of port patents owned	+	Chen et al. (2019a)
	Excellent Coastline (G3)	Length of coastline available for new excellent ports	+	Battino and Leonisio (2022)

4.2. Calculation method

The Best-Worst Method (BWM), introduced by Rezaei (2015), was chosen for several compelling reasons when considering its applicability to our study. The method offers a subjective approach to determining indicator weights, providing a more refined and focused evaluation. Unlike other methodologies, which might require exhaustive pairwise comparisons or are sensitive to inconsistencies, BWM narrows down the process by identifying the most crucial indicators – the best and the worst from a set. Evaluating them individually against the remaining indicators significantly streamlines what could otherwise be a tedious process. This approach reduces data volume, diminishing potential errors from handling excessive data. In addition, BWM inherently facilitates consistency tests, ensuring a more reliable set of weights as an outcome. While numerous methods are available for weight determination, BWM was deemed especially suitable for our research because of its ability to enhance precision and reliability without complicating the evaluation process. The specific steps involved in this method are outlined below.

Step 1: Select the most critical indicator D_B and least essential indicator D_W in the second-level indicators based on expert opinions.

Step 2: Determine the importance of the optimal indicator relative to other indicators using a scale of 1-9.

The two-by-two comparison of the relative importance of the optimal indicator and other indicators. The corresponding scales are obtained separately and expressed as comparison vectors $A_B = (a_{B1}, a_{B1} \cdots, a_{Bn})$. a_{Bj} denotes the importance of the optimal indicator D_B relative to indicator D_j; 1 means both are equally important, 9 means the optimal indicator is extremely important relative to the other.

Step 3: Determine the importance of other indicators relative to the worst indicator using a scale of 1-9. A two-by-two comparison of the relative importance of the worst and other indicators. The corresponding scales are obtained separately and expressed as the comparison vector $A_W = (a_{1W}, a_{2W}, \cdots, a_{nW})^T$. a_{jW} indicates the importance of indicator D_j relative to the worst indicator D_W; 1 indicates that both are equally important, 9 indicates that the former is extremely important relative to the worst indicator.

Step 4: A linear BWM model is used to derive the optimal indicator weights.

$$\min \max\{|w'_B - a_{Bj}w'_j|, |w'_j - a_{jW}w'_W|\}$$
$$s.t.\begin{cases} \sum_{j=1}^{n} w'_j = 1 \\ w'_j \geq 0 \end{cases}, (j = 1,2,\cdots,n) \tag{1}$$

where w'_B represents the subjective weight of the optimal indicator, w'_W represents the subjective weight of the worst indicator, w'_j represents the subjective weight of the indicator D_j. The model can be transformed into

$$\min \xi$$
$$s.t.\begin{cases} |w'_B - a_{Bj}w'_j| \leq \xi, (j = 1,2,\cdots,n) \\ |w'_j - a_{jW}w'_W| \leq \xi, (j = 1,2,\cdots,n) \\ \sum_{j=1}^{n} w'_j = 1 \\ w'_j \geq 0 \end{cases} \tag{2}$$

where ξ represents the deviation between the obtained weights and the ideal case where the pairwise comparisons are perfectly consistent. A smaller value of ξ, closer to 0, indicates a higher level of consistency among the pairwise comparisons, which in turn suggests that the obtained weights are more trustworthy and reliable. Solving equation (2) we obtain the optimal subjective weights of each evaluation criterion level indicator (w'_V, w'_C, w'_D, w'_G) and ξ.

Step 5: Solve for the optimal subjective weights of the indicator layer. Repeat steps 1-4 for different criterion-level evaluation indicators to find the optimal subjective weights $(w'_{V1}, w'_{V2}, \cdots, w'_{G3})$ and ξ, and judge whether it is plausible based on the ξ value. Finally, the optimal subjective weights w'_j of the indicator layer can be found.

4.3. Calculation results

We conducted focus group discussions with experts, including the 12 experts mentioned in Section 4.1 and others invited by them. We calculated the weights for each indicator using the Best Worst Method (BWM). Table 7 presents the results of the calculations.

Table 7. Results of the indicator weights

First-level indicators	Weight	Second-level indicators	Single sort weight	Total ranking weight
V	0.395349	V1	0.166667	0.065891
		V2	0.291667	0.11531
		V3	0.541667	0.214147
C	0.093023	C1	0.541667	0.050388
		C2	0.166667	0.015504
		C3	0.291667	0.027132
D	0.255814	D1	0.166667	0.042636
		D2	0.541667	0.138566
		D3	0.291667	0.074612
G	0.255814	G1	0.291667	0.074612
		G2	0.541667	0.138566
		G3	0.166667	0.042636

Table 7 serves as the crux of our research findings. The table's designations (V, C, D, G) correlate directly with those in Table 6. The “single sort weight” represents the weight of the second-level indicator within its respective first-level indicator. Also, the “total ranking weight” represents the weight of the second-level indicator within the overall evaluation framework. To better visualize these weights, we have employed a color-coding system. The maximum weight within each column is color-filled throughout the cell, while the remaining weights are shaded proportionally based on their value. According to the study of Rezaei (2015), we calculated the KSI of the first-level indicator to be 0.116279, with a CI (Consistency Index) of 1.63. We computed a CR (Consistency Ratio) value of 0.0232558. The KSI values for V, C, and D were all 0.041667, while the KSI for G was 0.166667, with a corresponding CI of 1. We found that the computed CR value was consistent with the KSI values, indicating that the consistency test was passed.

Table 7 shows that Vitality (V) holds the highest weight among the first-level indicators, highlighting the pivotal role of operational efficiency, safety, and automation, reflected by the second-level indicators under Vitality (V) in ensuring the robustness and competitiveness of smart ports. Within the Vitality (V) indicator, the high weight of the Uncrewed Level (V3) prominently underscores the transition towards automation as a hallmark of modern, efficient ports. This transition elevates operational efficiency and significantly minimizes human error, enhancing the safety quotient; another crucial aspect of the Vitality indicator.

The equal weights of Development (D) and Growing (G) reflect a balanced emphasis on sustainable internal growth and external collaborations. On the one hand, the high weight of Policy Environment (D2) within the Development (D) indicator underscores the necessity of a favorable policy landscape in promoting innovation and investments in smart port infrastructure. On the other hand, the emphasis on the R&D Level (G2) within Growing (G) accentuates the importance of continuous innovation and strengthening the intellectual property portfolio, which is vital for maintaining a competitive edge in the rapidly evolving maritime industry.

In contrast, the relatively lower weight attributed to the Coordination (C) indicator might reflect the secondary position of sustainability measures, such as energy savings and emissions reduction, in the face of more pressing operational and developmental priorities. This aligns well with the development trajectory of Tianjin Port, where the smart port initially focused on intelligence, followed by a gradual shift towards emphasizing sustainable development. However, within the Coordination (C) indicator, the higher weight of Energy Saving Level (C1) showcases a growing recognition of energy efficiency as a significant aspect of operational coordination, aligning with global sustainability goals and potentially leading to cost savings in the long run.

In this study, we refrain from ranking smart ports due to the sensitive nature of smart port data. Each port can integrate its data into the proposed evaluation framework to assess its current smart port health level. The following steps should be taken: First, obtain data corresponding to the evaluation framework indicators through internal port management system monitoring devices and statistical reports. Second, cleanse, organize, and normalize the collected raw data. Normalization can be achieved using linear or Z-score normalization to ensure data accuracy and comparability. The collected data should be combined with the indicator weights to calculate the scores of each indicator, subsequently deriving the port's comprehensive performance concerning vitality, coordination, development, and growth. The port's strengths and weaknesses can be identified based on the results of the analysis. Based on the evaluation results, port managers can establish clear development goals and devise appropriate optimization strategies and improvement measures to address the identified shortcomings. Data should be collected and evaluation results updated periodically to track the port's progress, monitor the implementation effects of improvement measures, and support the continuous optimization of the port's intelligent development.

5. Suggestions and conclusions

5.1. Suggestions for smart port development

The nuanced differentiation in the weights among these indicators provides a roadmap for prioritizing investments and initiatives in smart ports. By addressing the core aspects of Vitality and by balancing between Development and Growth while not losing sight of Coordination, smart ports can strategically navigate the pathway towards achieving operational excellence, sustainable growth, and enhanced competitiveness in the global maritime landscape. The case of Tianjin Port further confirms the soundness of this roadmap. The port’s development adheres to small-scale automation initially, followed by the development of a prototype smart port, thereby continuously improving the level of automation. In the third phase, the focus shifts to sustainability, reaching a smart carbon-zero port while also paying attention to its periphery, such as intelligent ships. Through the case of Tianjin Port and the evaluation framework, we suggest the development path of a smart port here.

1. In the initial phase of smart port development, the government's role is crucial in clarifying the top-level design and development planning for smart ports. For instance, the "Tianjin Smart Port Development Three-Year Action Plan (2017-2019)" released in February 2018, outlined five major categories and 29 key projects aimed at promoting the transformation, upgrading, and efficiency enhancement of Tianjin Port, providing a guide for regional smart port development. The government should follow a phased and gradual approach to ensure more robust and controllable development of smart ports. The new technologies involved in smart ports are still evolving and improving, so there might be technical bottlenecks and limitations (Baştuğ et al., 2020). A phased approach ensures that new technologies are thoroughly tested and validated, gradually maturing, while also helping to avoid financial strain and investment risks due to excessive initial investment. The development of smart ports requires substantial capital investment encompassing hardware facilities, software development, and system maintenance. These will also profoundly impact the port's organizational structure, management model, and operational processes. Hence, a phased smart port development approach is beneficial for timely adjustments and optimizations during organizational transformation, ensuring smooth implementation of reform measures.

2. For port managers, the development of smart ports is a long-term and systematically phased project, with each phase having its core focus and objectives. Technological upgrading and infrastructure development are the core tasks in the initial phase. Managers should prioritize the introduction of automation and digitalization technologies to enhance port operational efficiency (Lun et al., 2010). This includes amplifying investments in advanced technologies, optimizing data management and information-sharing platforms, and strengthening collaborations with relevant enterprises and research institutions to circumvent extended R&D cycles and high R&D costs, thus ensuring smooth technological upgrading. As the technological foundation gradually improves, port managers should progressively shift their focus toward environmental protection and sustainable development. In this phase, core tasks include implementing green port policies, optimizing port facilities and equipment, and establishing environmental and energy management systems. Through the implementation of green technologies and management systems, not only can the operational costs of ports be effectively reduced, but the social responsibility and brand image of ports can also be elevated, earning a better social reputation and market recognition. When smart port development matures, port managers should consider expanding the peripherals of smart ports, like the intelligent modification of waterways, to ensure safe navigation of vessels and attract more vessel berthings at the port. In this phase, summarizing and reflecting on previous development schemes to extract replicable and promotable successful experiences and models is essential for reducing development costs and improving efficiency in future expansion processes. Port managers should also closely monitor industry trends and policy changes to ensure smart port development aligns with policy directions and industry development trends, continually driving ports' smart and international development for long-term, sustainable growth.

3. For other smart port stakeholders, such as technology companies, research institutions, and industry organizations, their cooperation and innovation are also key to smart port development. Technology providers

should constantly update and optimize their technological solutions to meet the ever-changing demands of ports, actively participating in establishing and promoting standards to ensure their technological solutions comply with industry standards and norms, providing strong technical support for smart port development. Research institutions and universities should closely collaborate with ports, government, and technology providers to jointly conduct research and applications through cutting-edge technologies, promoting the innovation and development of smart port technologies. Moreover, industry organizations should play their coordination and guidance roles, facilitating cooperation and communication among all parties and providing a favorable industry environment and policy support for smart port development.

4. Recruiting and training talent are crucial steps in smart port development. Initially, ports should focus on attracting and training individuals skilled in advanced technologies and practical port operations to improve operational efficiency and modernization. Their skills will directly impact the safety and efficiency of port operations. Recruiting decision-makers with international experience and diverse backgrounds is important at a managerial level. Their global perspective can help build open and globally collaborative relationships, enhancing the port's competitiveness internationally. Their ability to think ahead and make strategic decisions is key for long-term planning and guiding the direction of smart and international port development. Ports should work closely with nearby universities and research institutions to improve talent training models, encourage interdisciplinary collaboration, and use advanced teaching methods like simulation and emulation systems to train well-rounded talent for the diverse development needs of ports. Besides focusing on internal talent development, building an external ecosystem is also important. Ports should collaborate with enterprises, universities, research institutions, and tech companies to nurture high-end maritime talent jointly and co-invest in technological innovation projects, creating a supportive, smart port development ecosystem. By fostering an open innovation ecosystem, ports can sustain development momentum, providing strong talent and technical support for building high-quality, efficient, eco-friendly smart ports.

5.2 Conclusions

This study advances the understanding of smart ports by elucidating their concept and comprehensively examining their composition, relationships, and evolution through an ecological lens. It offers a novel paradigm shift and perspective for future port and shipping research. We identify three components of smart ports—builders, supporters, and consumers—that collaboratively drive their development, informing the construction framework and highlighting the necessity for multi-party collaboration. Concerning evolution, smart port development is not a single-stage process but rather necessitates gradual progress and adequate groundwork in the preliminary stages, potentially following an intelligence-first, green-second development path. We redefine smart ports as ecosystems and introduce the notion of the health of smart ports. Building on this concept, we propose an evaluation framework for the health of smart ports comprising four primary and 12 secondary indicators.

This study forgoes scoring and ranking procedures due to challenges in obtaining smart port data. However, as smart ports evolve and data become available, we anticipate promising opportunities for future research. This study reinterprets smart ports with a focus on concept development. Incorporating ecology offers fresh insights for shipping researchers, who can explore additional key ecological concepts, such as ecological niche and ecological potential, to analyze smart ports' relative position in the shipping and trade system and their impact on it.

Appendix

Appendix A

Table A1 Definition of smart ports in the literature

Scholars	Definition (Original Text)	Main Perspectives
Rajabi et al. (2018 p.1415)	*"We define a smart port as a seaport well equipped and enhanced with technologies and innovations. In more detail, a smart port is a fully automated port where all devices are connected via IoT, data are properly gathered, processed, analyzed, and used by sensors, RFID, cloud/fog computing, and big data technologies, and finally, all of these are supported by different networks and IT infrastructures, like Local Area Network (LAN), Wide Area Network (WAN) and positioning systems."*	Technology integration, Automation
Triska et al. (2022 p.7)	*"We define a smart port terminal with real-time information handling capabilities that allow data-driven decision-making. This data-driven decision-making aspect is mentioned in the following subsection."*	Operational efficiency
Chen et al. (2019b p.1)	*"Smart port is based on systematic, strategic and social thinking, featuring integrated application of cloud computing, big data, Internet of Things, mobile internet, intelligent sensing, and other next-generation information technologies to achieve all-round perception, ubiquitous interconnection, intelligent integration, deep computing, and coordinated operation and promoting organic connection and sharing of various resource elements and related parties in the port organization ecosystem, to eventually form a modern port that is smarter, safer, more efficient, more flexible, greener, and with strong cultural presence."*	Technology integration
Gonzalez et al. (2020 p.1)	*"Smart Port is based on using new technologies to transform port services into interactive and dynamic, more efficient and transparent services. Its objective is to satisfy the customer and user needs and requirements. Moreover, port sustainability, from the environmental point of view, is included as a fundamental pillar, as well as its orientation toward the city and the citizen to provide quality spaces and services. Therefore, the Smart Port is designed to be fully integrated with the concept of the Smart City."*	Sustainability, Connectivity, and collaboration
Hsu et al. (2023, p.1)	*"Smart ports are ports that apply emerging technologies such as the Internet of Things, big data, and cloud computing to port operations and management, thereby allowing the ports to fully automate and efficiently complete the loading and unloading of cargo and directing ships to and from the port."*	Technology integration, Automation
Heikkilä et al. (2022 p.2)	*"We define the smart port as an automated, collaborative, and green port."*	Sustainability
Philipp (2020, p.51)	*"A smart port may be defined as a fully automated port where all devices are connected via IoT."*	Technology integration, Automation
Boullauazan et al. (2022 p.4)	*"Smart port is thus defined as a port that optimizes the in-, intra-, and outbound flow of goods and information, leads a sustainable development, and guarantees safe, resilient and secure activities through the capabilities of its (extended) port community and enabling technologies."*	Operational efficiency

Li et al. (2023 p.3)	*"We describe a smart port as a symbol of a higher level of port generation (Gen) with smart-technology-based solutions to help ports, port users, and the workforce improve their efficiency and activities, thus bringing benefits to both ports and the whole supply chain."*	Operational efficiency, connectivity, and collaboration

Appendix B

1. China Ports & Harbours Association

The China Ports & Harbours Association is the only national industry association for China's port sector, established with approval from the Ministry of Civil Affairs. It's a non-profit, cross-regional organization with over 750 members from major ports across China's coastlines and river systems. Supervised by the Ministry of Transport, it publishes "China Ports," a key monthly magazine for the maritime industry, and "Port Technology," a platform for sharing advancements in port and maritime technology. The association also compiles the annual "China Ports Yearbook."[7]

As shown in Table B1, the "Guidelines for Rating Evaluation of Smart Port - Container Terminals," published by the China Ports & Harbours Association, were developed in collaboration with significant contributors including the China Transport Telecommunications & Information Center, China Ports & Harbours Association, Shanghai International Port (Group) Co., Ltd., Shandong Port Group Co., Ltd., China Merchants Port Group Co., Ltd., Tianjin Port (Group) Co., Ltd., and the Transport Planning and Research Institute of the Ministry of Transport in Tianjin. The evaluation system is organized into 3 first-level indicators, 7 second-level indicators, and 25 third-level indicators.

Table B1 Guidelines for rating evaluation of smart port - container terminals

First-level Indicator	Second-level Indicator	Third-level Indicator
Facility Equipment	Production Facilities and Equipment	Automated Loading and Unloading
		Intelligent Operating Systems
		Intelligent Gates
		Intelligent Tallying
	Informational Facilities	Perception
		Network
		Big Data Center
		Information Security
Information Technology	Data and Interfaces	Data Standardization
		Interface Standardization
	Technology Integration	Internet of Things System
		Geographic Information System
		Intelligent Surveillance System
		Mobile Applications
		Technology Convergence
Intelligent Digital Services	Implementation Effects	Loading and Unloading Efficiency
		Shoreline Utilization
		Cost per Container
		Energy Conservation and Environmental Protection
	Logistics Services	Online Business Processing

[7] http://english.chinaports.org/about/index.html

	Electronic Documentation
	Collection and Distribution System
	Customer Service
Regulation Coordination	Information Sharing
	Business Collaboration

Notes: This table is taken from section 5 of the original text.

2. China Institute of Navigation

The China Institute of Navigation, founded in 1979, is a national, academic, non-profit organization affiliated with the Ministry of Transport and managed by the China Association for Science and Technology. It brings together navigation professionals and related entities to advance nautical science and technology. The institute plays a crucial role in supporting China's development as a leading maritime, technological, transportation, and shipping power. It publishes "Navigation Technology" and "China Navigation", focusing on promoting advanced navigation techniques, safety, environmental stewardship, and enhancing the efficiency of shipping enterprises.[8]

As shown in Table B2, the China Institute of Navigation has released the "Evaluation Indices for Intelligent Port." This system was collaboratively drafted by the Ministry of Transport's Water Transport Research Institute, Shandong Port Qingdao Port Group Co., Ltd., Shanghai International Port (Group) Co., Ltd., and the Shanghai Broadband Technology and Application Engineering Research Centre. The evaluation framework encompasses 5 first-level indicators and 19 second-level indicators.

Table B2 Evaluation indices for intelligent port

First-level Indicator	Second-level Indicator
Infrastructure	Network
	Data
	Security
Business Units	Production Unit
	Management Unit
	Service Unit
Business Integration	Production Integration
	Management Integration
	Service Integration
Business Collaboration	Collaboration with Regulatory Departments
	Collaboration with External Business
	Intermodal Transport Collaboration
	Internal Department Collaboration
Quality and Efficiency	Safety
	Benefit
	Efficiency
	Service Quality
	Reliability
	Environmental Protection and Energy Saving

[8] https://www.cinnet.cn/en/xhgk_e/profile

Notes: This table is taken from Fig. 2 of the original text.

Appendix C

We synthesized information from the International Transport Forum (2021) and Majoral et al. (2024) to present the current landscape of automated container terminals, as shown in Table C1. In the column titled "Type of Automation," "Full" refers to full-automated container terminals, while "Semi" denotes semi-automated container terminals. A container terminal is classified as full-automated when both the stacking yard and the horizontal transfers between the quay and the yard are automated. In contrast, a terminal is considered semi-automated when automation is implemented within the stacking yard but does not extend to a comprehensive integration with the quay operations.

Table C1 Automated container terminals in the world

Terminal	Port	Country	Type automation	Since
ECT Delta	Rotterdam	Netherlands	Full	1993
Pasir Panjang	Singapore	Singapore	Semi	1997
Thamesport	London	United Kingdom	Semi	2000
APMT-R	Rotterdam	Netherlands	Full	2000
Altenwerder	Hamburg	Germany	Full	2001
Fishermans Island	Brisbane	Australia	Semi	2002
Wai Hai	Tokyo	Japan	Semi	2003
Evergreen Marine	Kaoshiung	China	Semi	2005
DPW Gateway	Antwerp	Belgium	Semi	2007
Korean Express Busan	Busan	South Korea	Semi	2007
Virginia International	Portsmouth	United States	Semi	2007
Tobishima Pier South	Nagoya	Japan	Full	2008
Euromax	Rotterdam	Netherlands	Full	2008
Newport (Hanjin, HMM)	Busan	South Korea	Semi	2009
Newport (DPW)	Busan	South Korea	Semi	2009
Isla Verde	Algeciras	Spain	Semi	2010
Burchardkai	Hamburg	Germany	Semi	2010
Kao Ming	Kaoshiung	China	Semi	2010
Taipei Port CT	Taipei	China	Semi	2010
Khalifa CT	Abu Dhabi	United Arab Emirates	Semi	2012
BEST	Barcelona	Spain	Semi	2012
London Gateway	London	United Kingdom	Full	2013
DP World	Brisbane	Australia	Semi	2014
HPH Brisbane	Brisbane	Australia	Semi	2014
SSA Manzanillo Int.	Colon	Panama	Semi	2014
Jebel Ali 3	Dubai	United Arab Emirates	Semi	2014
TraPac	Los Angeles	United States	Semi	2014
Global Terminal	New York	United States	Semi	2014
Lamong Bay	Surabaya	Indonesia	Semi	2014
SICT-HPH	Sydney	Australia	Semi	2014

Yuan Hai	Xiamen	China	Full	2014
APMT-MV2	Rotterdam	Netherlands	Full	2015
Rotterdam World Gateway	Rotterdam	Netherlands	Full	2015
PPT	Singapore	Singapore	Semi	2015
Patrick Stevedoring	Sydney	Australia	Semi	2015
Hanjin Incheon CT	Incheon	South Korea	Semi	2016
APMT	Lazaro Cardenas	Mexico	semi	2016
Liverpool 2	Liverpool	United Kingdom	Semi	2016
Middle Harbor	Long Beach	United States	Semi	2016
Victoria International CT	Melbourne	Australia	Full	2016
Tuxpan Port Terminal	Tuxpan	Mexico	Semi	2016
Yangshan Phase 4	Shanghai	China	Full	2017
Qianwai CT	Qingdao	China	Full	2018
Ferguson Terminal	Auckland	New Zealand	Semi	2019
Belfast Container Terminal	Belfast	United Kingdom	Semi	2019
Tanger Med 2	Tanger	Morocco	Semi	2019
Tianjin FICT	Tianjin	China	Full	2019
AMPT	Vado Ligure	Italy	Semi	2019
Vizhinjam Port	Vizhinjam	India	Semi	2019
Haifa Bay Terminal	Haifa	Israel	Full	2021
Beijiang C	Tianjin	China	Full	2021
Mawan	Shenzhen	China	Full	2021
Long Beach CT	Long Beach	United States	Semi	2021
APMT	Los Angeles	United States	Semi	2021
Norfolk International Terminal	Virginia	United States	Semi	2021
Tianjin Second Port Container Terminal	Tianjin	China	Full	2022
Nabeta (Nagoya)	Nagoya	Japan	Semi	2023
Tuas Container Terminal Phase 1	Singapore	Singapore	Full	2040

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