Journal of Information Systems Engineering and Management
2025, 10(34s)

e-ISSN: 2468-4376

https://www.jisem-journal.com/

Research Article

Overview and Future Trends of Intelligent Technology Applications of Smart Ports in China

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ARTICLE INFO

Received: 18 Dec 2024

Revised: 10 Feb 2025

Accepted: 28 Feb 2025

ABSTRACT

Ports play a crucial role in sustaining human society. In recent years, the rapid development of China's ports, along with the swift growth in container throughput, has brought significant pressure on port management. As a result, smart ports have garnered widespread attention from scholars and practitioners. This study evaluates the current state of smart port research using scientometric methods, analyzing literature from the Web of Science Core Collection. The focus is on balancing technology, environmental sustainability, and economic development. Key findings reveal that current research trends emphasize integrating advanced technologies like Internet of Things (IoT) and Digital Twin (DT), enhancing energy efficiency, and driving digital transformation in port operations. The study identifies three main research directions: the application of Information and Communication Technology (ICT), environmental sustainability, and safety in multimodal transport systems. It also highlights the evolution of research themes from 2001-2015focusing on Infrastructure upgrading. 2016-2020 focuses on big data and pollution. 2021-2024 with an emphasis on smart ports and sustainability. The research direction of smart ports trends to evolve and gradually adapt to the needs of global technological innovation, multimodal logistics, management and sustainable development. The paper provides insights into key thematic categories, influential authors and journals, and emerging trends, offering valuable guidance for new researchers in the smart port field.

Keywords: Smart Port, ICT, Intelligent Technology, Scientometric Method, CiteSpace

INTRODUCTION

The advent of Industry 4.0 technologies has led to the integration of advanced tools such as artificial intelligence (AI), the Internet of Things (IoT), Digital Twin (DT), blockchain, and 5G in ports worldwide. AI, IoT, Digital Twin, Blockchain, and 5G collectively enhance port operations by enabling predictive decision-making, real-time monitoring, secure data exchange, and ultra-fast communication, which streamline logistics, improve efficiency, and ensure operational safety (De La Peña Zarzuelo et al., 2020). This technological convergence has driven the emergence of smart ports, which in turn has intensified competition and accelerated China's digital transformation in port infrastructure (Aliyev, 2022). Major coastal ports in China rely heavily on Information and Communication Technology (ICT), including IoT, AI, big data, and cloud computing, to enhance efficiency, automation, and intelligence in port operations. The automation of equipment, intelligent scheduling, and data visualization significantly reduce logistics, labor, and management costs, driving a comprehensive upgrade that enhances global competitiveness for ports (Bruno, 2023; Kok-Lim Alvin Yau et al., 2020; Rahaman, 2018; Sun, 2021).

The academic community is increasingly focused on smart port technologies due to their crucial role in national economies. With 80% of world trade transported by sea, effective management of the port logistics chain is vital (Kok-Lim Alvin Yau et al., 2020; Millefiori et al., 2016). Scholars highlight the importance of ICT in enhancing port performance, particularly through information systems supporting container handling processes (Bakari Omari

Journal of Information Systems Engineering and Management
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Bakari & Subriadi, 2020). Concepts like "smart port-hinterland integration," involving coordinated pre-planning, scheduling, and monitoring, illustrate the potential for ICT to synchronize activities and adapt to disruptions efficiently (Yuri Triska et al., 2019).

Despite the benefits, applying ICT in port automation faces controversies and challenges. Smart sensing systems and IoT technologies are pivotal in current and future port developments across regions, from Europe to North America (Yongsheng Yang et al., 2018). However, the impact of ICT on port competitiveness varies. Some studies show ICT significantly influences supply chain coordination and competitiveness, while its impact on supply chain integration is less pronounced (Tai-yuan, 2012). In developing economies, ports face constraints such as low ICT investment, lack of skilled manpower, and inadequate integrated facilities, hindering the adoption of ICT (Bakari Omari Bakari & Subriadi, 2020); M. O. Aponjolosun & Ogunsakin, 2021; and Jiang et al., 2023).

To address these complexities, this paper aims to analyze the impact of ICT on port operations through a scientometric analysis. The specific objectives are:

(1) To identify the status of new technology applications in smart ports using a co-occurrence network of discipline categories from 2001 to July 2024 and analyze smart ports development trends.

(2) To explore the development levels of Chinese ports through co-occurrence keyword analysis and co-citation analysis. Highlight sudden changes and emerging trends in the field by analyzing advancement in ICT.

LITERATURE REVIEW

The development of global ports has gone through five generations. The first generation served primarily as nodes for sea and land transportation. The second generation focused on deploying infrastructure and equipment, reducing reliance on manpower. The third generation transformed ports into cargo handling centers. The fourth generation breaks the physical isolation of the port by enhancing port network services, meaning it overcomes the traditional limitations of ports being disconnected from broader transportation and logistics networks. This shift is crucial as it enables seamless communication between ports, inland transportation, and global supply chains, enhancing efficiency and reducing delays. By integrating ports into broader digital and logistical networks, they can more effectively respond to market demands and global trade dynamics. The fifth generation focuses on creating smart ports that prioritize customers and trade centers. This generation integrates advanced technologies like IoT, AI, and big data to enhance decision-making, optimize operations, and provide personalized services. By prioritizing customer needs and optimizing trade processes, it transforms ports into dynamic hubs that drive global trade and economic growth, laying the foundation for more sustainable and efficient operations. In September 2006, China promulgated the National Plan for the Layout of Coastal Ports, dividing its ports into five large areas (Lee et al., 2018).

The Definition of Smart Port

Ma Weiwei, differentiates "smart ports" from other related concepts, emphasizing its holistic, organic, and responsive nature, rather than a mere addition of emerging information technologies (Ma Wewei, 2018). Xie Xilin defines smart ports as those utilizing advanced technologies like artificial intelligence, cloud computing, the Internet of Things, and precise positioning for comprehensive perception, extensive sharing, deep computation, intelligent applications, and broad connectivity (Xie Xilin, 2019). Yu Shiyuan, Chen Fang, Yang Jianjin interpret the connotations of smart ports from three levels: daily operations, strategic management, and green ecology, going beyond technical applications to analyze facility intelligence, port-city integration, and green sustainability (Yu Shiyuan, Chen Fang, Yang Jianjin., 2020). Rahman focusses on developing a framework and metric, the Smart Port Index (SPI) emphasizing ICT applications and regulation-based approaches to enhance port resiliency and sustainability (Rahman, 2023). Additionally, Molavi defines a smart port as a modern and technologically advanced port utilizing innovative technologies and data-driven solutions to enhance operational efficiency, safety, and sustainability, encompassing four main activity domains: operations, environment, energy, and safety and security (Molavi et al., 2020).

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e-ISSN: 2468-4376

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Based on the literature review and the study's objectives, a smart port means the application of innovative technologies to address challenges in modern facilities, including improving operational efficiency, enhancing sustainability, reducing environmental impact, increasing safety and security, and managing supply chain complexities (Belmoukari et al., 2023; Molavi et al., 2020). Smart port leverages ICT to enhance knowledge sharing and connectivity, enabling comprehensive perception and information sharing. Smart ports deploy IoT devices and sensor networks throughout the port to monitor conditions in real time. AI-driven systems might adjust container stacking processes to minimize movement time, maximizing crane productivity and reducing fuel use. Blockchain technology ensures secure, transparent data exchange among stakeholders, including shipping companies, customs, and logistics providers. 5G provides the high-speed, low-latency connectivity needed for real-time data sharing and remote operation of equipment. By using 5G networks, ports can securely connect thousands of IoT devices and systems, enabling seamless data flow and enhanced responsiveness. By leveraging these ICT components, smart ports achieve seamless information sharing and comprehensive perception across all operations, leading to safer, faster, and more cost-effective handling of goods. The goal is to improve operational efficiency and environmental sustainability, making the port more efficient, convenient, environmentally friendly, and secure.

Distinctions Between Traditional Ports and Smart Ports

Various scholars have provided diverse insights into the definition and connotations of smart ports. Since 2008, major hub ports globally have introduced the concept of "smart ports," making it a focal point of research (Zhou Haoqing, 2022). Theoretically, smart ports involve using the latest technology to address various port-related issues. Traditional ports often face bottlenecks in logistics and cargo handling, leading to delays and high turnaround times. In conventional setups, communication among stakeholders (e.g., port operators, logistics providers, customs, etc.) can be slow, resulting in uncoordinated activities. Traditional ports often lack real-time tracking of goods, leading to miscommunication and delays in the supply chain. Practically, smart ports utilize intelligent technology to coordinate and interact across all stages of the port supply chain. Shi Duo states that the development of smart ports is grounded in traditional ports, employing innovative development models in conjunction with rapidly advancing scientific and technological trends. This approach facilitates the optimized transformation of port enterprises within emerging development trajectories (Lytvyn et al., 2023; Shi Duo, 2018).

Table 1. Distinctions Between Smart Ports and Traditional Ports

Observed Dimensions	Traditional Port	Smart Port	Smart Port Advantages
Production operation mode	Closed operations, closed loading/unloading of goods	Open operations, collaboration across supply chains, focus on innovation and expansion	Production capacity, operational efficiency
Technologica l innovation	Limited to certain processes with minor efficiency gains	Comprehensive innovation driven by data and intelligent management	Technology application, operation management, innovation ability
Core goal of construction	Meeting the operational demands	Facilitating international trade	International, connected
Labor demand	Labor intensive, large workforce, minimal skill requirements	Tech-intensive, smaller workforce, high skill requirements	Intelligent, professional personnel
Economic benefits	Low economic benefits, high energy consumption	High economic efficiency, green and low carbon, aligns with national environmental goals	Green, low carbon, efficient and environmental protection

Source: Adapted from Lytvyn et al., 2023; Shi Duo, 2018

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Note: Table 1 was constructed by the author based on the referenced sources.

Table 1 contrasts smart ports with traditional ports across several dimensions: operational mode, technological innovation, construction goals, labor demand, and economic benefits. Smart ports emphasize open collaboration efficiency, technological innovation, and environmental sustainability, representing a significant departure from the labor-intensive, low-efficiency model of traditional ports.

Smart Port Policy for Development Promotion

The14th "Five-Year Plan" development Plan of China's water transport puts forward the development direction of smart ports, including digital channels, green ports, safe ports, scientific and technological innovation, and channel technology upgrading. In December 2023, China's Ministry of Transport proposed accelerating the development of smart ports, aiming for enhanced digitization and intelligence in port infrastructures by 2027. This initiative includes integrating technologies like cloud computing, big data, IoT, AI, and blockchain. The concept of smart ports in China began in January 2017, focusing on intelligent logistics and safety management. In 2019, a port development indicator system with 16 metrics was established to guide major ports and enterprises in pilot projects aimed at building a logistics hub powerhouse. In 2021, the Action Plan for New Infrastructure in Transportation was put forward aimed at automating terminal operations, creating a smart logistics platform, and improving coordination among port stakeholders. The overall goal is to enhance operation efficiency, logistics management, and safety, in line with national strategies to strengthen port capabilities and support economic growth.

ICT in Smart Port Applications

The Definition of ICT

(Kok-Lim Alvin Yau et al., 2020) addresses the intense global competition faced by ports in the digital era, emphasizing the role of Smart Ports in enhancing competitiveness and sustainability through the application of ICT. The study reviews literature on Smart Ports, covering IoT platforms, greenhouse gas reduction, and energy efficiency improvements. conduct a survey on Port Center Information and Communication Technology Systems (PCIS) centered on how internal and external information integration, port community operational capabilities, and port performance are interrelated and impact overall port performance.

M. O. Aponjolosun & Ogunsakin highlight the increasing significance of ICT in the global maritime industry, noting that many ports are adopting ICT to improve operational management and productivity. Ports management is heavily invested in ICT infrastructure to enhance efficiency, attract customers, and meet higher service quality demands (M. O. Aponjolosun & Ogunsakin, 2021). Smart ports, as high performing ports, utilize information and communications technology (ICT) to provide a wide range of smart applications, resulting in vastly improved vessels and container management among others, which subsequently improve the competitiveness and sustainability of the national economy. Qingdao Port research confirms that internal information integration plays a pivotal role in improving port performance. A port should commence its digitalization journey with internal information integration, then move towards building effective information links with its existing and new community members (Jiang et al., 2023). Tianjin Port put forward the construction of new automated terminals, upgrading of traditional terminals, and comprehensive digital transformation. The increasing digitalization is not only driven by efficiency gains (e.g., reducing cargo transit time and port congestion), but also by safety, security, and environmental concerns (He Hongcai, 2022). However, Nigerian ports face challenges such as low budget allocations, insufficient ICT personnel, poor ICT maintenance culture, and lack of integration of ICT facilities with other port stakeholders (M. O. Aponjolosun & Ogunsakin, 2021). A study on the development of port information systems for the Beibu Gulf Port has emerged as a critical focus for its future growth. However, a notable research gap exists in the current performance evaluation system for such systems. The existing framework is insufficient for driving targeted improvements in the efficiency and capabilities of port services and information system construction (G. Liu et al., 2022).

Application Status of ICT in Smart Ports

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e-ISSN: 2468-4376

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Table 2. Application Status of ICT in Smart Ports

Key Elements	Definition/Description	Benefits for Ports	References
AI	Systems simulating human intelligence using various techniques	- Enhances container handling efficiency - Enables yard automation through AI and ML at terminal gates. - Improve customer service and reduce the turnaround time. - Classifies cargo and recognize Heavy Goods Vehicles (HGV) via AI based Ocean Freight (OFR) - Enhances safety through AI image recognition by monitoring high-risk port areas - Streamlines gate operations with automated ticketing for drop/load location.	(Rahman, 2023c) (Team, 2021)
IoT	A network of interconnected devices that collects and shares data via the internet and make data-driven decisions without requiring human intervention	- Monitors ships operations and risks with IoT sensors. - Supports predictive maintenance for ships, including engine performance, fuel consumption, temperature, and hull integrity. - Improves port management efficiency and reduces congestion - Enhances port security and prevents cargo theft.	(*Next-Generation Maritime Connectivity*, 2023)
DT	A virtual representation of physical entities using real-time data and advanced analytics	- Optimizes vessel maintenance and fuel efficiency which could drive down costs and emissions released - Simulates supply chain scenarios for better operations. - Enhances scheduling and cost savings in shipping	(*The Promise (and Peril) of Digital Twins for Ports*, 2023) (Rahman, 2023) (Bruno, 2023) (Team, 2022)
Blockchain	A decentralized digital ledger for transparent and secure data management	- Enables real-time shipment tracking and reduces delays thus minimizing potential disputes and fraud. - Automates processes with smart contracts, thus minimizing paperwork and use of human resources. - Optimizes supply chains by identifying inefficiencies and bottlenecks. - Facilitates automated verification and secure data sharing.	(Rahman, 2023)
5G	Latest and most advanced wireless communication technology	- Upgrades yard and container handling equipment with 5G. - Automates terminal operations using L4 autonomous driving technologies for	(Yagmur Yigit et al., 2023)

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	providing high-speed, low-latency connections.	horizontal transportation guided by the Bei Dou Navigation Satellite systems setting as a new standard for upgrading traditional container terminals worldwide. - Enhances supply chain visibility and decision making. - Provides real-time data for time-sensitive operations.

Table 2 highlights the critical role of ICT in port and logistics operations, addressing issues related to infrastructure, efficiency, sustainability, and stakeholder communication in the context of global maritime competition and digital transformation.

METHODOLOGY

Data Acquisition

Figure 1 illustrates the process of bibliography data extraction. The Web of Science (WoS) was chosen for scientometric data sampling due to its strong and consistent impact on the scientific community, particularly through its core collections, including the Science Citation Index Expanded (SCI-EXPANDED), Social Sciences Citation Index (SSCI), Arts & Humanities Citation Index (A&HCI), and Emerging Sources Citation Index (ESCI) (Cabeza-Ramírez et al., 2021).

A preliminary search was conducted using the search code TS = (smart port/ports* AND technology application), with synonyms refined based on peer-reviewed literature and articles. The final search query, TS = (smart port /ports*or seaport) AND (technology application or new technology), resulted in the retrieval of 371 papers.

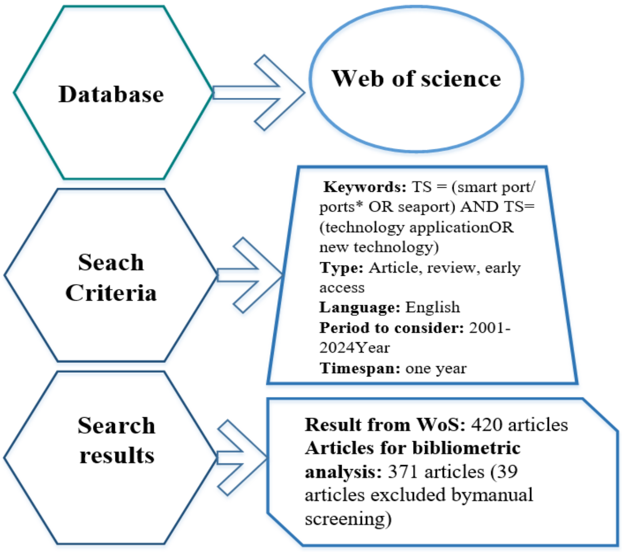

Figure 1. Bibliography Data Extraction

Figure 2 presents detailed information on the bibliographic references provided from 2001 to July 2024. The annual publication volume reflects the theoretical level and development speed of the smart port research field. Smart port research began in 2000, with different development trends at each stage. Between 2000 to 2010, research on smart ports remained steady with relatively fewer publications. After 2010, there was a slow upward trend, reaching a peak of 70 publications in July 2024, showing a rapid overall increase. The number of publications in 2023 was seven times higher than in 2013. This surge is attributed to the global recognition in 2010 that port development had entered the fifth era, known as Generation-Smart Ports (Lee et al., 2018; Molavi et al., 2020). In 2013, China proposed the Belt and Road Initiative, which included investments in international port infrastructure. With the promotion of information and communication technology, port intelligent upgrades have been continuously advancing, leading to an unprecedented research boom in smart port studies.

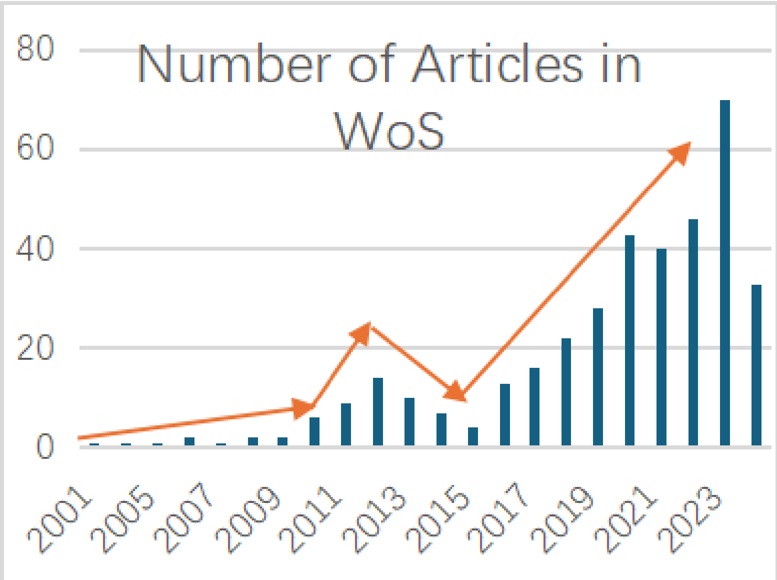

Figure 2. The Number of Papers Published from 2001 to July 2024

Source: processed primary data

CiteSpace

CiteSpace, initially released as a research prototype on September 25, 2003, has evolved through versions 2.0 (2005), 3.0 (2011), 4.0 (2015), and 5.0 (2016). This study uses the latest version, 6.3, released in June 2024. CiteSpace, a Java application, generates visualizations of knowledge domains, offering significant problem-solving advantages over earlier tools. It answers questions about the structure and dynamics of a knowledge domain by modeling it with various time series networks. CiteSpace visualizes patterns and trends, revealing shifts in research focus, interconnections between fields, and the evolution of research areas. With its clear, user-friendly interface, CiteSpace employs three core concepts—burst detection, betweenness centrality, and heterogeneous networks. These features address practical issues like identifying research fronts, highlighting keywords, and spotting emerging trends. Nodes and links form the visual mappings represent analytical objects and their relationships. Nodes with purple rings indicate high centrality, while burst detection highlights nodes with high change rates using red rings, identifying areas of professional interest and research fronts. (C. Chen, 2017, 2018)

Co-citation analysis refers to the frequency with which two articles are cited simultaneously in another article. This section applies document, author, and journal co-citation networks together with the clustering analysis. Based on the 371 records from the primary data processed between 2001 to 2024, accurate visualization of each network is shown in the corresponding section (Panayides & Song, 2008).

This study identifies influential authors, popular journals, key research topics, and major research areas in smart port research by analyzing journal publication volume, authors, institutions, keyword co-occurrence, clustering, bursts, and timeline graphs. This further analyzes the development trends of smart ports.

RESULTS AND DISCUSSION

Co-citation Analysis: Author Co-citation Analysis

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e-ISSN: 2468-4376
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The author collaboration network analysis identified 359 nodes and 398 connections. Each node represents an author,while each connection indicates a cooperative relationship between authors. In a co-authorship network, if two authors co-sign a paper, a line is established between them. The 398 connections here represent 398 collaborations between these 359 authors. As shown in **Figure 3**, the author collaboration network is relatively sparse, primarily forming three research collaboration groups: Mondragon, Adrian E Coronado; Mondragon, Christian E Coronado and Carrasco, Raul; Chen, Chen; Camarero-Orive, Alberto and Chen, Jihong; Mondragon, Etienne S Coronado. Among these, Mondragon, Adrian E Coronado and Mondragon, Christian E Coronado are particularly prominent. However, the overall network remains relatively dispersed, with no significant collaboration network established among researchers.

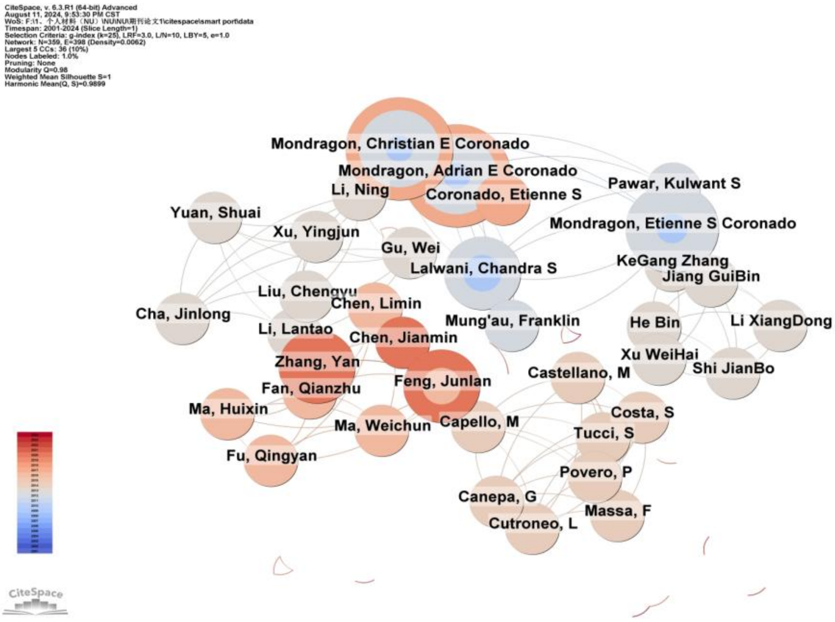

Figure 3. The Author Collaboration Network

To identify influential authors in the field of smart ports, the top 10 authors with the highest number of publications and citations are listed in **Table 3**. Chen Jihong ranks first with 34 citations, followed by Heilig Leonard with 33 citations, and Molavia with 31 citations. These authors are among the key figures in pioneering the definition of smart ports and their comprehensive indicator systems (Belmoukari et al., 2023; J. Chen et al., 2019; Molavi et al., 2020). Other highly cited authors include Sun You-Gang (29), Hvattum Lars Magnus (28), and Yang Yongsheng (19). Tracking these highly cited authors helps identify popular topics and emerging research frontiers in the field.

Table 3. Top 10 Authors with the Highest Number of Publication and Most Frequently Cited in the Smart Port Area

Highest Number of Publication			**Most Frequently Cited Authors**		
Author	Year	No.	Author	Year	Frequency
Mondragon, Adrian E Coronado	2009	4	Chen, Jihong	2019	34
Mondragon, Christian E Coronado	2009	4	Heilig, Leonard	2017	33
Carrasco, Raul	2021	3	Molavia	2021	31
Chen, Chen	2021	3	Sun, You-Gang	2017	29
Camarero-orive, Alberto	2020	3	Hvattum, Lars Magnus	2015	28

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Chen, Jihong	2019	3	Geerlings, Harry	2019	23
Mondragon, Etienne S Coronado	2009	3	Yang, Yongsheng	2018	19
Duran, Claudia	2024	2	Carrasco, Raul	2021	18
Abdelwahab, H S	2023	2	Chen, Chen	2021	17
Kumar, Nishant	2023	2	Castellano, Rosalia.	2019	15

Note: No.-Number of Publications

Subject Category Co-occurrence Network

The Subject category co-occurrence network, shown in Figure 4, consists of 68 nodes and 178 connections, representing the research topics in the field of smart ports, including 57 distinct classes, highlighting the multidisciplinary area of the study. The size of the nodes represents the number of papers on each topic, while the magenta outer ring of the nodes indicates the topic's centrality.

Figure 4 highlights the 11 most common themes in the current research within this field, including sustainable science, engineering, environmental studies and sciences, science and technology, green and sustainable engineering, and oceanography. These themes illustrate that smart port research is beginning to extend into areas such as engineering, science and technology, and marine ecological environmental issues. Maintaining the balance between technology, the environment, and economic development is crucial. However, "Green & Sustainable Science & Technology" has emerged as a key theme in smart port research as it has the Strongest Citation Bursts.

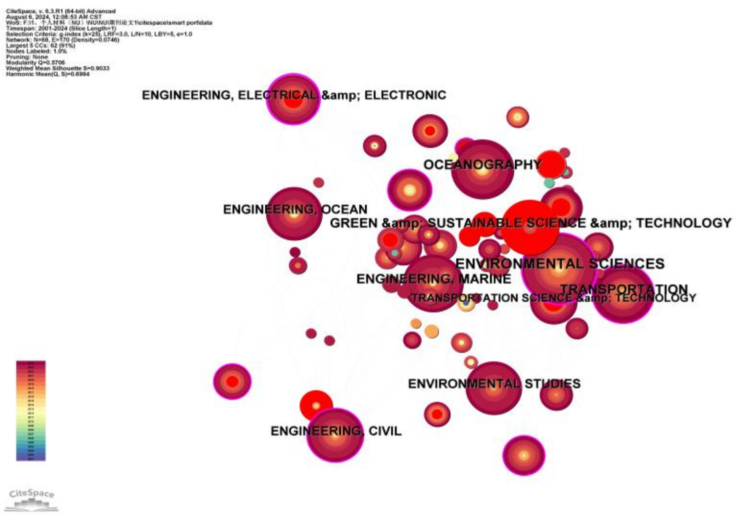

Figure 4. Co-occurrence Network of Subjects with High Frequency in the Smart Port

Institutions Category Co-occurrence Network

Figure 5 illustrates the co-occurrence network of research institutions, comprising 294 nodes and 214 connections. The network exhibits a notable clustering effect, with a concentration of academic research in smart ports within a few key institutions. Notably, Shanghai Maritime University has published 19 high-quality articles related to smart ports since 2017, highlighting its significant contribution to the field.

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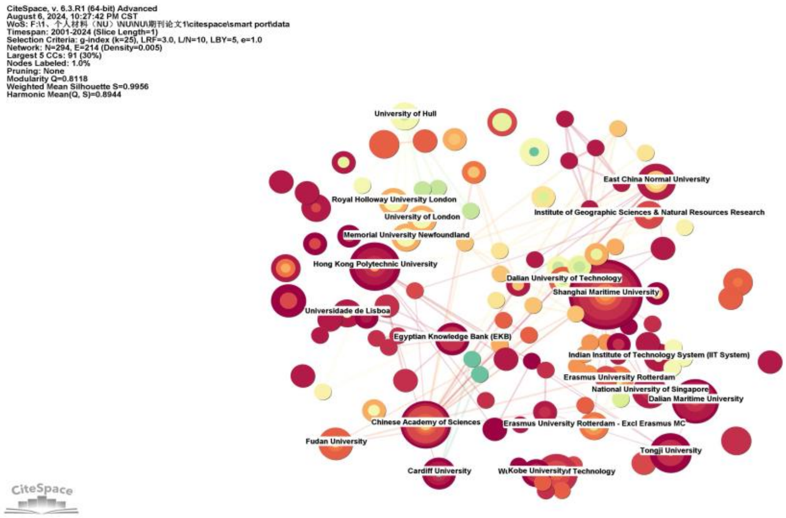

Figure 5. The Co-occurrence Network of Research Institutions

Table 4 reveals that the majority of the literature on smart ports is attributed to universities and research institutions, with fewer coming from enterprises, administrative institutions, and other units. Of the 107 papers published by 20 research institutions, 71 were from 8 institutions, representing 66% of the total. This phenomenon reflects that although countries around the world are conducting research on smart ports, China demonstrates a high-level of enthusiasm. The academic research on smart ports in China is in a state of flourishing development.

Table 4. Top 20 Most Cited Articles and the Associated Institutions

Rank	Articles	Year	Institution	Country
1	19	2017	Shanghai Maritime University	China
2	10	2013	Chinese Academy of Sciences	China
3	9	2013	Hong Kong Polytechnic University	China
4	8	2020	Dalian Maritime University	China
5	6	2017	Tongji University	China
6	6	2020	Wuhan University of Technology	China
7	5	2012	East China Normal University	China
8	4	2022	National University of Singapore	Singapore
9	4	2016	Fudan University	China
10	4	2021	Universidad Tecnologica Metropolitana	Chile
11	4	2006	Cardiff University	Britain
12	4	2022	Egyptian Knowledge Bank (EKB)	Egypt
13	3	2011	Istanbul Technical University	Türkiye
14	3	2013	Universidade de Lisboa	Portugal
15	3	2010	Erasmus University Rotterdam	Netherlan ds
16	3	2020	Universidad Politecnica de Madrid	Spain
17	3	2021	Fahrenheit Universities	Poland
18	3	2019	Delft University of Technology	Netherlan ds
19	3	2022	Ho Chi Minh City University of Transport	Vietnam
20	3	2012	Indian Institute of Technology System (IIT	India

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	System)

Document Co-citation Network

The document co-citation network highlights key research that significantly impacts the field of smart ports, characterized by innovation, universality, and academic collaboration. **Table 5** lists the top 10 most cited papers, which focus on the integration of advanced technologies such as the Internet of Things (IoT), enhancing energy efficiency, and driving digital transformation to improve port operations and governance. These studies also explore the development of frameworks and indices for assessing smart port capabilities, as well as the economic impact and specific challenges associated with implementing these innovations in various port environments.

Table 5. Top 10 References with the Strongest Citation Bursts

Strength	Reference	Rank	Journal	Author& Year
5.84	Towards Smart Port Infrastructures: Enhancing Port Activities Using Information and Communications Technology	1	IEEE	(Kok-Lim Alvin Yau et al., 2020)
4.39	Constructing Governance Framework of a Green and Smart Port	2	Journal of Marine Science and Engineering	(J. Chen et al., 2019)
3.78	A review of energy efficiency in ports: Operational strategies, technologies and energy management systems	3	Renewable and Sustainable Energy Reviews	(Iris & Lam, 2019)
3.53	Digital transformation in maritime ports: analysis and a game theoretical framework	4	Netnomics: Economic research and electronic networking	(Heilig et al., 2017)
3.46	Internet of Things and business processes redesign in seaports: The case of Hamburg	5	Business Process Management Journal	(Ferretti & Schiavone, 2016)
3.34	Preparation of a Smart Port Indicator and Calculation of a Ranking for the Spanish Port System	6	Logistics	(Rodrigo González et al., 2020)
3.23	Impact of the smart port industry on the Korean national economy using input-output analysis	7	Transportation Research Part A: Policy and Practice	(Jun et al., 2018)
3.07	Identifying the unique challenges of installing cold ironing at small and medium ports – The case of Aberdeen	8	Transportation Research Part D: Transport and Environment	(Jun et al., 2018)
2.98	Internet of things for smart ports Technologies and challenges	9	IEEE Instrumentation & Measurement Magazine	(Yongsheng Yang et al., 2018)
2.9	A framework for building a smart port and smart port index	10	International journal of sustainable	(Molavi et al., 2020)

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Co-word Analysis

This section uses co-word analysis to illustrate and analyze several research themes related to smart ports and technology applications, using data from the WoS database. The analysis focuses on two primary networks: the subject category co-occurrence network and keyword co-occurrence network.

Keyword Co-occurrence Network and Burstiness

Keywords provide a condensed summary of a paper's core content. This paper constructs a keyword co-occurrence graph using the top 10% of most frequent keywords from each year. In the graph, connection lines transition from deep blue to yellow over time, with node size representing keyword frequency. **Figure 6** shows the keyword co-occurrence network, with 397 nodes and 1284 links. The size of the nodes corresponds to the frequency (f) of keyword appearances. The 15 most frequent keywords are: smart port(s) (f = 40 times), model (f = 26 times), management (f = 25 times), challenges (f = 19 times), technology (f = 17 times), system (f = 14 times), impact (f = 13 times), internet (f = 13 times), framework (f = 12 times), sea (f = 11 times).

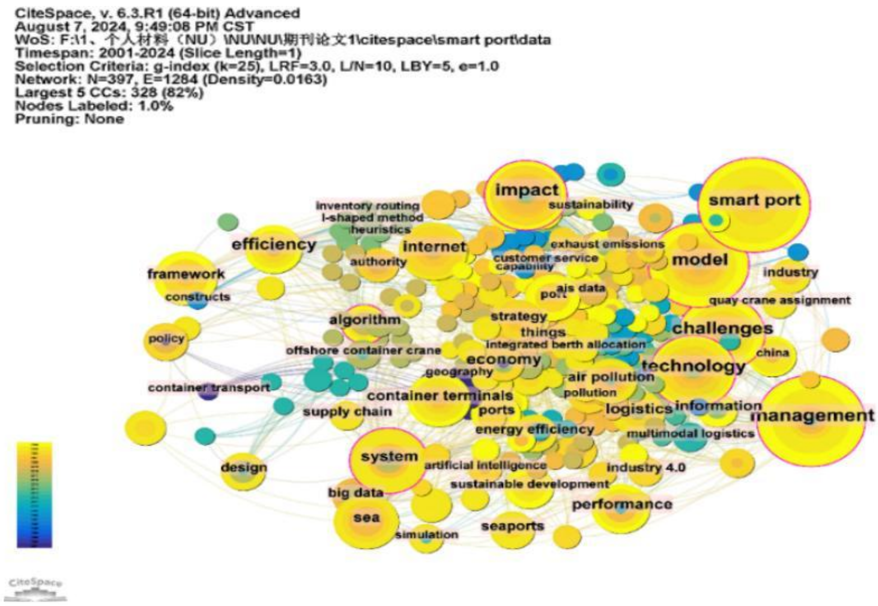

Figure 6. Keyword Co-occurrence Network

From the analysis of these keywords, it is evident that there are challenges in the development and upgrading of smart ports. Understanding the factors influencing the transition from traditional ports to smart ports is essential, such as technology, management, information communication, and systems. Additionally, numerous studies focus on specific issues such as container operations, efficiency, and environmental concerns in smart ports. Therefore, smart ports should not be viewed from a single perspective. The analysis reveals that the strong correlation between keywords contributes to the diversity of current smart port research.

Explosiveness indicates the most important research areas, as the number of citations increases rapidly in a short period. **Figure 7** analyzed a total of 19 keywords with the strongest citation bursts being detected. The top 5 keywords with the highest burst strengths are: smart port (burst strength = 4.31, 2020-2024), strategy (burst strength = 2.83, 2021-2022), system (burst strength = 2.19, 2017-2018), internet (burst strength = 2.13, 2018-2022), and big data (burst strength = 2.05, 2016-2020), along with their respective periods of occurrence.

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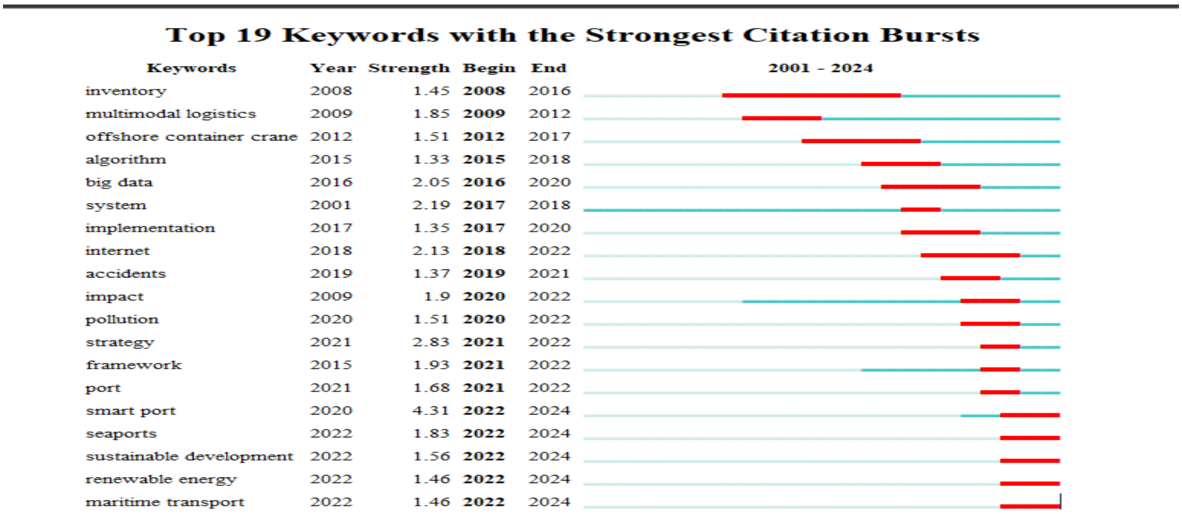

Figure 7 Knowledge map of the keyword cluster

To more accurately identify research topics in the field of smart ports and understand their development trends, the burst characteristics of the above keywords reveal that research on smart ports is concentrated in three directions:

1.The application of information and communication technologies such as the internet, communication systems, and big data.

2. Environmental sustainability, including the use of renewable energy to promote the sustainable development of smart ports.

3. Issues related to the safety of multimodal transport logistics systems, maritime transportation, and container operations.

Cluster Visualization Keyword Co-occurrence Network

Each color area in **Figure 8** represents a clustering topic, with larger areas indicating more keywords. The size of the areas is adjusted based on the number and density of nodes in the cluster. A larger area means that there are more keywords or literature focused on the topic, indicating a higher level of interest in the topic in the field of research. The clustering is automatically generated based on the co-occurrence relationship of keywords or the co-citation relationship of documents. The areas size is proportional to the number of cluster nodes, The weighted algorithm follows the log-likelihood ratio (LLR), ensuring the accuracy of the clustering. The high modularity score of Q = 0.6465 (Q > 0.3) indicates that the clustering is effective, with topics being divided into ell-defined, loosely coupled clusters (He et al., 2017). From the figure, we can see that N=397, E=1284; Q=0.6465, S=0.8642. A Q value greater than 0.5 and an S value greater than 0.7 indicate that the figure is meaningful. As shown in **Figure 8**, the keyword clustering map illustrates the different research focus in this field. There are 10 labels in the figure, representing 10 clusters. Each cluster label corresponds to keywords in the co-occurrence network, and the cluster numbers range from #0 to #9. The larger the cluster number, the fewer key terms it contains; conversely, the smaller the number, the more keywords the cluster includes. Most connections within the map are within clusters, but there are still some connections across clusters. Among them, 0 (big data), #1 (crowdsourcing), #2 (IoT), and #3 (multimodal logistics) have more cross-cluster connections, indicating a high degree of co-citation between these research directions.

Journal of Information Systems Engineering and Management
2025, 10(34s)

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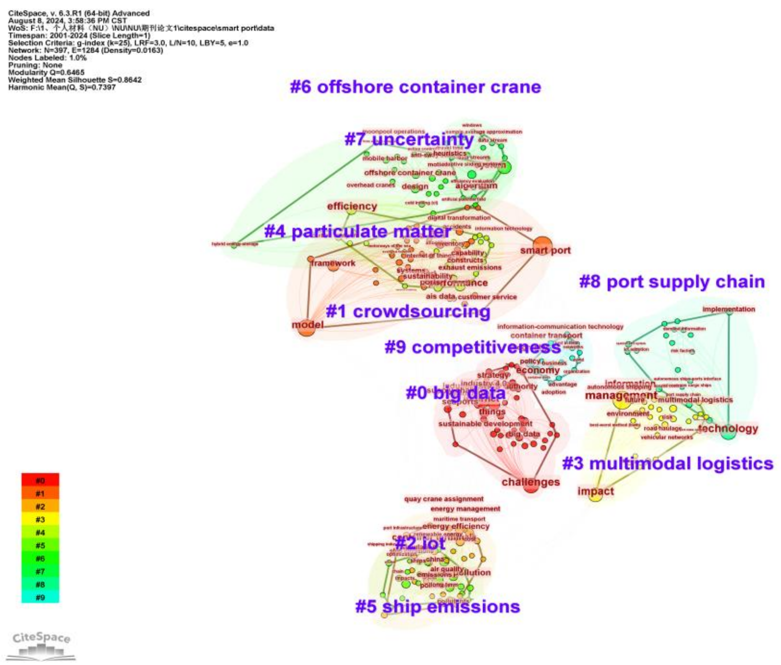

Figure 8. Cluster Visualization Based on the Document Co-citation Network of 2001–2024

Table 6 provides detailed information on the 10 clusters. A cluster size smaller than 10 indicates relatively poor clustering effectiveness. The Silhouette value represents homogeneity, meaning the closeness of internal members; a value greater than 0.7 indicates good tightness, suggesting successful clustering. The Mean (Cite Year) indicates the average citation frequency of keywords per year.

The most recent structure consists of some of the largest clusters, such as #0 (big data), 1 (crowdsourcing), and #2 (IoT). The mid-term structure primarily includes #5 (ship emissions), 7 (uncertainty), and #8 (port supply chain). The earlier structure consists of clusters labeled as #3 (multimodal logistics), 4 (particulate matter), 6 (offshore container crane), and #9 (competitiveness).

Table 6. Top 10 Key Co-citation Clusters Based on Frequency in Smart Port

Cluster ID	Size	Silhouette	Label (LLR)	Mean (Cite Year)	Representative Literature
0	52	0.767	Big Data	2020	(Castellano et al., 2019) (Pagano et al., 2022) (Pham, 2023)
1	46	0.746	Crowdsourcing	2020	(Durán et al., 2024). (Wang et al., 2021) Yang et al., 2024)
2	36	0.734	IoT	2019	(Gao et al., 2022) (Coronado Mondragon et al., 2017) (Gekara & Thanh Nguyen, 2018)
3	30	0.943	Multimodal Logistics	2011	Coronado Mondragon et al., 2009) (M. Liu et al., 2024)
4	28	0.926	Particulate Matter	2012	(Ezeh et al., 2024)
5	25	0.922	Ship Emissions	2018	(Fan et al., 2016; Zhou et al.,

					2020)
6	23	0.932	Offshore Container Crane	2014	(Ngo & Hong, 2012) (Ngo et al., 2017)
7	22	0.956	Uncertainty	2016	Agra et al., 2015)
8	19	0.92	Port Supply Chain	2016	(Coronado Mondragon et al., 2017) (Rodrigo González et al., 2020) (Y. Liu et al., 2022)
9	18	0.923	Competitiveness	2005	(S.-Y. Lee et al., 2016) (Airriess, 2001).

In summary, the largest clusters research trends in smart ports focus on advancements in big data, crowdsourcing, ICT, and innovative technologies. Big data plays a key role in ship navigation, logistics, passenger transport and environmental sustainability, ensuring that ports are at the forefront of the fourth Industrial Revolution (Castellano et al., 2019) (Pagano et al., 2022) (Pham, 2023). Crowdsourcing leverages broad stakeholder engagement to enhance the reliability and efficiency of blockchain, digital twins and machine learning systems, while ICT is reshaping the port's operating model and workforce structure through the decentralization of real-time tracking and data management (Durán et al., 2024). The mid-term structure primarily an in-depth look at key challenges and cutting-edge solutions in the field of smart ports and their related supply chains (Rodrigo González et al., 2020). Through the application of smart contracts, these technologies have significantly restructured the business processes of the port supply chain, enabling a more efficient and transparent operating model (Agra et al., 2015) (Fan et al., 2016). The earlier structure consists of clusters labeled focus on smart ports and the transformation of the global port transport industry, demonstrating the key role of ICT in driving supply chain efficiency, environmental strategies, and port competitiveness (Ngo & Hong, 2012) (M. Liu et al., 2024; Zhou et al., 2020).

The development trend of smart ports can be summarized by Cluster Visualization Keyword Co-occurrence Network in different stages: The latest trend emphasizes the application of big data, crowdsourcing and IoT technology to promote the intelligent operation and efficiency of ports. Medium-term trends focus on reducing ship emissions, addressing supply chain uncertainty, and optimizing port supply chain business processes through smart contracts. Early trends focus on intermodal logistics, particulate emissions, intelligent container cranes, and increased port competitiveness. These technologies and environmental measures work together to make ports more efficient, transparent and sustainable.

Cluster Visualization of Keywords Timeline

A Keywords Timeline Chart shows how keywords or concepts in a topic or field have changed over time. This type or chart helps to understand research trends, thematic evolution and hot issues. **Figure 9** shows that each circle in the graph represents a keyword and the year it first appeared in the analyzed dataset. If the keyword reappears in subsequent years, its frequency increases by 1 at the point of its initial appearance. If a keyword appears several times, its frequency increases accordingly, causing the corresponding keyword circle to expand in size.

Journal of Information Systems Engineering and Management
2025, 10(34s)

e-ISSN: 2468-4376

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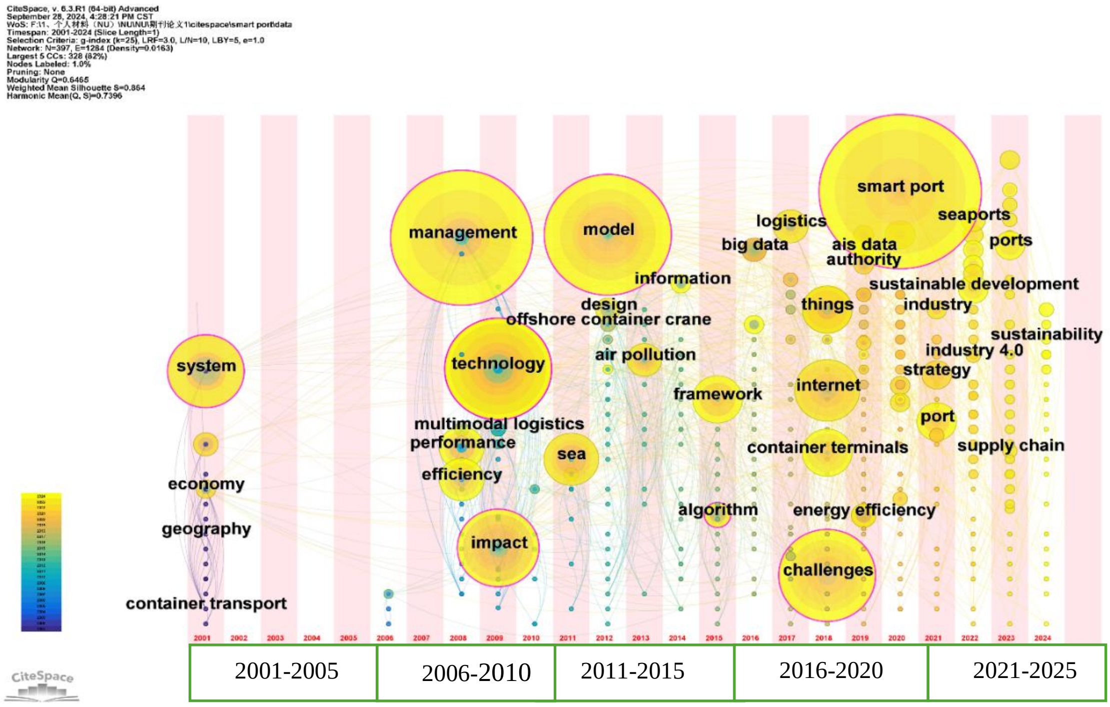

Figure 9. Knowledge Map of Keywords Timeline.

Table 7 clearly shows a surge in smart port research since 2020. The main research focuses on the keywords of "Economy", "infrastructure", "technology", "logistics and supply chain", "management", "sustainable development", "smart port", and so on, which are the research hotspots and development trends. The technology research of China Smart port mainly focuses on the keywords of "big data", "information technology" and "Industry 4.0". Since 2006, technology first appeared in the keyword of port research, the application research of "digitalization", "informatization" and "sustainable development" of smart port technology has continuously shown new progress.

Table 7. Knowledge of Keyword Development Timeline

Keywords / Period	**Economy, Performance, Energy efficiency**	**Transport, Offshore container crane, Terminals**	**Technology, Big data, Internet Things, Information, Industry4.0**	**Multimodal logistics, Logistics, Supply chain**	**Management, Strategy**	**Air Pollution, Sustainable Development, Sustainability**	**Smart Port**
2001-2005	•	•	–	–	–	–	–
2006-2010	•	0	•	•	•	–	–
2011-	0	•	•	0	0	•	–

Journal of Information Systems Engineering and Management
2025, 10(34s)

e-ISSN: 2468-4376

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2015							
2016-2020	•	•	•	•	o	o	•
2021-2025	N/A	N/A	•	•	•	Θ	N/A
Note: • - Year Start, o - Year Continue, Θ - Year Start in 2021 & 2024, N/A - Not Applicable							

Table 8. Key Words of China's Port Development Policy

Keywords Period	**Infrastructure**	**Logistics Efficiency**	**Green Port**	**ICT**	**Digital Transformation**	**International Cooperation**
11th Five-Year	√					
12th Five-Year	√	√				
13th Five-Year			√	√	√	
14th Five-Year			√	√	√	√

Table 8, the perspective of China's Development Policy, indicates that the smart port planning in the next 15th Five-Year will focus on digital transformation, ICT technology application, Sustainable Science and Infrastructure development.

This change shows that the research direction of smart ports trends is evolving and gradually adapting to the needs of global technological innovation, multimodal logistics, management and sustainable development.

CONCLUSION

In conclusion, smart port research has evolved significantly, focusing on balancing technological advancements with environmental and economic considerations. The current emphasis on "Green & Sustainable Science & Technology" highlights a strong interest in integrating advanced technologies such as IoT, DT enhancing energy efficiency, and driving digital transformation in port operations.

This study has identified three fundamental research themes within the field of smart port development:

1. Integration and Impact of Digital Transformation Technologies: This encompasses the application of ICT, including the internet, communication systems, and big data, as well as the impact of digital transformation on various aspects of port operations such as efficiency, environmental sustainability, energy management, safety, and security. Both qualitative and quantitative assessments are crucial for understanding these impacts.

2. China's port development is transitioning from basic technical management to full digital transformation through advanced ICT technologies. China's port development has progressed from the basic technology management and policy implementation of the 12th Five-Year Plan (2011-2015) to the extensive application of big data and IoT technology in the 13th Five-Year Plan (2016-2020). In the 14th Five-Year Plan (2021-2025), advanced technologies such as blockchain, IoT and DT are driving the digital transformation of port supply chain management. The rapid advancement and application of ICT technology has enabled smart ports to make important breakthroughs in addressing global supply chain challenges and environmental issues, marking emerging trends and sudden changes in the field. These changes include enhanced real-time data sharing across supply chains, reduced carbon emissions through automated and optimized operations, and the integration of sustainable practices that align with global environmental standards.

3. **Challenges and Barriers to Development**: This addresses the key challenges and obstacles faced in the development of smart ports, including issues related to multimodal transport logistics, maritime transportation, container operations, and environmental sustainability. Solutions to these challenges are vital for advancing smart port capabilities.

This study lays a foundation for future research by identifying key thematic areas and potential pathways. Current research mainly explores the feasibility of new digital technologies in port operations. However, broader adoption of these technologies requires addressing challenges related to transparency, collaboration, and trust, using case studies as valuable references. Additionally, while smart ports have significant potential to benefit from these technologies, a comprehensive performance evaluation is essential to assess how these advancements will promote smart port development.

Academic and Practical Significance:

Academically, this study enhances the understanding of the concept of smart ports, addressing the lack of a precise definition. It also provides an overview of publication trends, influential authors, and the leading institutions and countries in smart port research through bibliometric analysis. The study identifies key issues and research themes in the field, revealing directions for future research.

Practically, the findings of this study will support port stakeholders in better understanding the issues related to smart port development, enabling them to make critical decisions regarding the application of advanced technologies to improve port performance.

Limitations of the Study:

This study has several limitations. Firstly, relying solely on the Web of Science database may overlook relevant research found in other databases such as Scopus and Google Scholar. Secondly, focusing on journal articles may have excluded gray literature, conference papers, and non-English publications. Gray literature, which includes reports, government documents, and industry publications, is valuable as it often provides current insights, practical data, and case studies not typically found in peer-reviewed journals. Including this literature could offer a broader understanding of real-world applications and emerging trends in smart port research. Thirdly, the study's evaluation of only 371 papers reflects the early stage of smart port development and may limit the scope of bibliometric analysis. Future studies are encouraged to include multiple databases and publications, to provide a more comprehensive view of the evolving field of smart ports.

Acknowledgement

This research is supported by the Guangxi University Young and Middle-Aged Teacher Scientific Research Basic Ability Improvement Project (No. 2021KY0639), the Guangxi First-Class Discipline Statistics Construction Project Fund, and the 2021 Special Project on Innovation and Entrepreneurship Education in Universities, under the "14^{th} Five-Year Plan" for Education Science in Guangxi, China (Project No. 2021ZJY1433).

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