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ARTICLE

Industry 4.0 research in the maritime industry: a bibliometric analysis

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Abstract

Industry 4.0 (I4.0) is currently a major topical concern in the literature on maritime industry. Maritime 4.0 is the area concerned with the integrated implementation of digital processes and technologies in the maritime industry. There is, however, a shortage of review studies that can reflect the research directions and various important issues in Maritime 4.0. The purpose of this study is to explore and categorize academic publications concerned with Maritime 4.0 to identify its current research status, main subject categories, emerging trends, current gaps, and future research directions. To provide a comprehensive review of the publications, the study used bibliometric analysis to conduct citation analysis (publication distribution, productive journals, and cross-country collaborations), cooccurrence of the subject categories, cocitation analysis, and keyword frequency analysis. In doing so, the study utilized the Web of Science (WoS) dataset and software packages for data analysis. Finally, the study proposed a research framework composed of five themes to link current research topics with future research trends in Maritime 4.0. The five themes observed were "digitalization technology," "methodology and techniques," "management," "safety and security," and "environmental issues." The results revealed that, although scholars and practitioners focused on Maritime 4.0, this area remained underdeveloped. Many scopes under the five themes were left unexplored, such as emerging paradigms of Internet of things (IoT) and blockchain under the theme of "digitalization," hybrid models (e.g., game theory and genetic algorithms) under the theme of "methodology and techniques," and social responsibility under the theme of "environmental issues."

Keywords Maritime industry · Industry 4.0 · Maritime 4.0 · Bibliometric analysis

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1 Introduction

The notion of Industry 4.0 (I4.0) was first introduced in 2011. As a revolutionary process, I4.0 seeks to integrate various dimensions of information and communication technology (ICT) while promoting digitalization and information-driven industrial development (Mohd Salleh et al. 2021). I4.0, also known as the Fourth Industrial Revolution, underscores the digitalization of manufacturing industries. The transformation of organizations to the digital form (digitalization), is commonly known as Industry 4.0 (Sony and Naik 2020). The two terms *Industry 4.0* and *digitalization* are strongly interrelated because digitalization majorly contributes to the implementation of I4.0 (Jahn and Saxe 2017). As such, digitalization will be the main driver of innovation and transformation in the near future.

There is, however, no universal definition of I4.0. Some researchers have viewed it as a process increasing digitization and automation in the manufacturing industry. Some others, foregrounding an outcome-oriented perspective, suggest I4.0 represents a new stage or paradigm for industrial production. Other scholars have referred to I4.0 as an umbrella term for new technologies and technological concepts. The transition to I4.0 can crucially impact manufacturing firms' ability to gain competitive advantage and to seize new opportunities (Weking et al. 2020).

By adopting such a paradigm, smart manufacturing systems will work in an interconnected but decentralized environment that can adapt their production processes to market demand. The achievement of such a status, of course, demands relying on key enabling I4.0 technologies including the Internet of things (IoT), big data, artificial intelligence (AI), simulation, autonomous robots and systems, mobile augmented reality, additive manufacturing, cloud computing, 3D printing, and cybersecurity (Rüßmann et al. 2015).

Since its inception in 2011, I4.0 has proven to be a topical concern in theory and practice. I4.0 practices have been employed in different industrial sectors including the maritime industry. The impacts of I4.0 are becoming more evident in the integral aspects of the maritime industry including shipping, shipbuilding, seaports, and terminals. Maritime transport shapes the backbone of global trade and the global economy. More than 80% of the world's merchandize trade is carried by sea (of course, in 2020, international maritime trade and global supply chains were strongly damaged by the impacts of the COVID-19 pandemic, UNCTAD 2021). The integrated implementation of digital processes and technologies in the maritime industry is known as *Maritime 4.0* (Sullivan et al. 2020). Maritime 4.0 seeks to redesign supply chains in the maritime industry through digitalization and interlinking (Jahn and Saxe 2017). This process brings about significant advantages such as generating new value, fostering cooperation between port actors, reducing operational cost, and increasing total revenue (Aiello et al. 2020; Di Vaio and Varriale 2020).

To further reinforce itself, the maritime industry has developed several I4.0 initiatives on a global scale. For example, the Port of Hamburg has launched an initiative to implement smart seaport logistics using cloud-based tools (Mohd Salleh et al. 2021). Meanwhile, Qingdao, Shanghai, Rotterdam, and Singapore have introduced autonomous shipping (Jeevan et al. 2021). Existing reports have also mentioned the implementation of blockchain initiatives at the Port of Long Beach, the Port of Rotterdam, and some Indonesian ports (Munim et al. 2021). Such ports as Hamburg and Rotterdam have been investing in Industry 4.0, identifying themselves as *smart* ports (Di Vaio and Varriale 2019). Currently, the term "Port 4.0" is a trending topic in the industry (De la Peña Zarzuelo et al. 2020). Port 4.0 generally describes a digital port that functions as a hub for physical and informational flows in global supply chains, interconnecting all the actors involved (Jahn and Saxe 2017).

However, despite the importance of I4.0 and its topical status in Maritime 4.0, there is a shortage of studies addressing the integration of I4.0 in the maritime industry. In fact, research on this area is still going through its developmental stages, and for this reason, there are evident gaps in the literature on this topic (Fruth and Teuteberg 2017; Sanchez-Gonzalez et al. 2019; Munim et al. 2020). Only a few review studies have explored the literature on I4.0 in the maritime industry. The available literature reviews have either concentrated on specific I4.0 technologies (De la Peña Zarzuelo et al. 2020; Munim et al. 2020, 2021) or addressed the integration of I4.0 and sustainability issues (Jeevan et al. 2021; Del Giudice et al. 2022). For instance, Munim et al. (2020) focused on research on big data and AI in the maritime industry, identifying the research clusters through a bibliographic coupling analysis. Del Giudice et al. (2022) also investigated the application of digitalization in the construction of sustainable business models.

From a methodological viewpoint, a content analysis of publications in this field revealed that only three review studies (Del Giudice et al. 2022; Jeevan et al. 2021; Munim et al. 2020) applied bibliometric analysis. In their review studies, Fruth and Teuteberg (2017) and Sanchez-Gonzalez et al. (2019) drew on systematic literature review to determine the current status of digitalization in maritime transport. Munim et al. (2020), of course, observed that the literature search procedure that Sanchez-Gonzalez et al. (2019) employed seemed subjective and was not easily replicable. Generally speaking, the existing reviews addressed a limited scope and were not methodologically powerful. More robust efforts are needed to explore I4.0 in maritime studies and to provide a broader picture of the key themes, emerging trends, and future directions in this field.

The purpose of this study is to explore the literature on I4.0 in maritime studies. The study seeks to identify current research trends in this field through bibliometric analysis. The main research directions in the field are also identified based on the bibliometric results and a content analysis of the most important cited papers. Contrary to previous research, the present investigation includes publications that have dealt with all I4.0 technologies in the maritime industry. The present study traces the evolution of different themes in this area of research, trying to provide more reliable results by considering various bibliometric items. In response to the shortcomings in the literature, this study provides four main contributions: (a) it documents the development of research on Maritime 4.0 over the years; (b) it provides a detailed overview of the existing literature, introducing the most influential journals, articles, and authors, along with collaboration networks of countries exploring this field; (c) through the document cocitation analysis, the study identifies the founders, seminal works, clusters of documents, and key concepts in the realm of Maritime 4.0; and (d) using keyword frequency analysis, the study investigates the emerging research topics in terms of five key themes it identifies.

The study is guided by four research questions: How has research on I4.0 in the maritime industry evolved over time? What are the overall publication trends and academic collaborations in research on Maritime 4.0, what are the countries and journals exploring Maritime 4.0, and who are the authors concerned with this area of studies? And, what are the future research directions addressing Maritime 4.0? Finally, based on the results of the bibliometric analysis and a content analysis of 27 cited papers, the study highlights the gaps and possible future research directions. It also proposes a research framework to link the current research topics with the future research directions. The remainder of this paper is organized as follows: Section 2 details the methodological approach. Section 3 presents the results and discussion, and Section 4 reports the concluding remarks.

2 Research method

Bibliometric analysis is a research methodology that enables researchers to unpack the evolutionary aspects of a specific field, shedding light on the emerging areas in the field in question. It can identify collaboration patterns, research clusters, and knowledge gaps, uncovering the intellectual structure of a specific domain and its emerging trends (Donthu et al. 2021).

This study used bibliometric analysis to investigate the current status, key themes, and gaps in research on Maritime 4.0 and to predict future research directions in this field. A bibliometric analysis would effectively help to explore a fragmented research scope such as Maritime 4.0. To answer the research questions specified, the study pursued the following four-step process (see Fig. 1).

Step 1: Identify the search strings. To find the search strings, the majority of the existing literature review studies concerned with the maritime industry and I4.0 were inspected and analyzed.

In doing so, the initial keywords were identified from other publications (Lau et al. 2017; Fiskin and Cerit 2020; Del Giudice et al. 2022). The keyword "port number" was excluded from the list as it could represent such disciplines as electronics and telecommunications, instead of maritime studies (Munim et al. 2020). Keywords related to I4.0 were also included as a research criterion. Various keywords appeared in the literature on I4.0, which was first publicly introduced in Germany in 2011 as "Industrie 4.0" to refer digitalization in industry (Thoben et al. 2017). This study included other commonly related terms such as "digitalization," "smart manufacturing," "smart factory," and "smart port." These concepts have all stemmed from I4.0.

The idea of the smart port also emphasizes the automation of port operations and equipment, as well as the interconnection of the entire port logistics chain (Douaioui et al. 2018). A smart port is a fully automated port where all devices are connected via an IoT platform. The main infrastructural components of a smart port are sensors and actuators, wireless devices, and data centers (Yang et al. 2018).

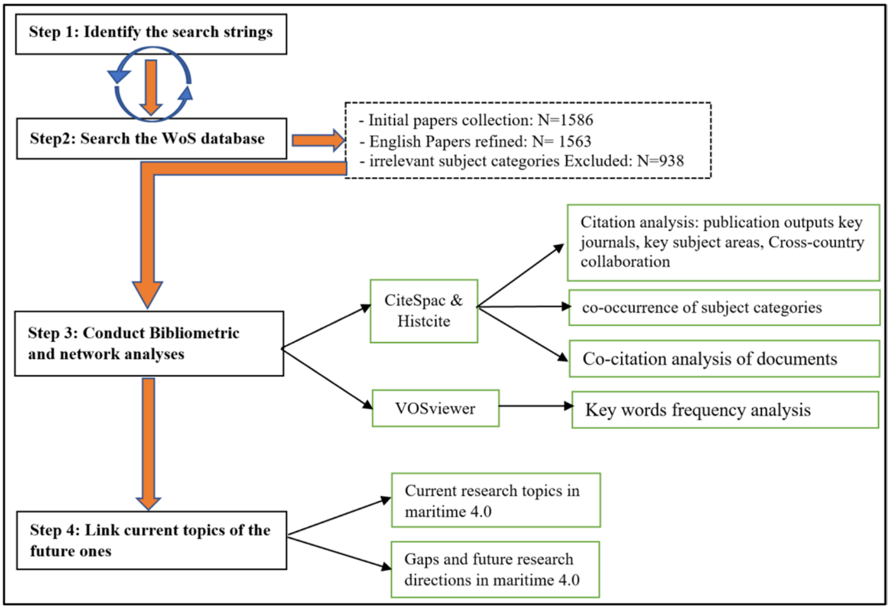

Fig. 1 The research procedure

Finally, the analysis process included the keywords related to I4.0 technical enablers (IoT, cyber-physical systems, etc.). Table 1 shows the list of the finalized queries representing Maritime 4.0.

Step 2: Search the WoS database. The search strings collected were then searched on the WoS database. In the case of document cocitation analysis, the search procedure involved records published between 2011 and December 2021. In the case of keyword frequency analysis, however, records published between 2001 and 2022 were searched. To obtain a strongly representative set of search strings, the initial keywords were inspected and updated through an iterative process, based on the contents of the publications found.

The WoS database was selected for the search procedure because it made it possible to search current and retrospective multidisciplinary publications (Rey-Martí et al. 2016; Song et al. 2019). Because I4.0 was first introduced as a concept in 2011, the year 2011 was set as the starting point. The initial search yielded 1586 records. The topic field on the WoS database was searched using the keywords, and only publications written in English were included. To address new discussions concerned with Maritime 4.0, all types of documents including journal articles, book chapters, and conference proceedings were included in the analysis process. Accordingly, the refined search procedure found 1563 records.

Some irrelevant subject categories in maritime studies were also omitted, such as fisheries and biology. Applying the Refine Results option of the WoS database showed a total of 938 relevant publications for analysis. Next, the search results were

Table 1 The search strings representing I4.0 in maritime studies (a three-echelon search structure)

Field	Search string keyword
Maritime	seaport* OR Port Or Ports OR "sea-port*" OR "Ship port interface" or "sea- port" OR "short-sea" or "port industry" OR "sea trade" OR Harbor* or Harbour* OR "harbour operation" OR " harbor operation" OR "port operation" OR Maritime* OR ship* OR shipping OR "Short Sea shipping" OR "Ship-port" OR "port generation" OR "Container terminal" OR "container port" OR "container ports" OR "Sea Transport"* OR "Marine Transport*"
Industry 4.0	AND Industry4.0 OR "industry 4.0" OR I4.0 OR "I 4.0" OR "industr* 4.0" OR "fourth industr*" OR " industr* revolution 4.0" OR Digital* OR "Digital Technolog*" OR "Digital* transformation" OR "smart Manufactur*" OR "Smart Factor*" OR "Smart port" OR "Internet of thing*" OR IoT OR "Internet of service*" OR "artificial intelligence" OR "Big Data" OR "Cloud comput*" OR "blockchain" OR "blockchain" OR "Cyber-physical systems" OR "virtual reality" OR "Augmented Reality"
	AND NOT "Port number*"

exported and stored for subsequent analysis in CiteSpace, HistCite, and VOSviewer software packages. CiteSpace and HistCite software programs required the search results to be in plain text format. However, to prepare the data format for VOSviewer, the WoS records were exported into a tab-delimited file.

Step 3: Conduct bibliometric and network analyses. In this step, citation analysis was conducted in CiteSpace (5.8.R3) and HistCite, to detect publication trends, the key journals, and the most influential countries. Meanwhile, the analysis investigated the cooccurrence of the subject categories and computed the cocitation analysis of the publications addressing Maritime 4.0. VOSviewer was used to calculate the frequency of the keywords and thus revealed the topical concerns explored in the literature on Maritime 4.0.

Step 4: Link current topics to future ones. A research framework is proposed to link the current research topics to future research directions based on the bibliometric analysis results and the content analysis of the top 27 most cited documents.

The data used for analysis were obtained from the following WoS indices: "Science Citation Index Expanded (SCI-EXPANDED)" (1980-Dec 2021), "Social Sciences Citation Index (SSCI)" (1980-Dec 2021), "Arts & Humanities Citation Index (A&HCI)" (1975-Dec 2021), "Conference Proceedings Citation Index-Science (CPCI-S)" (1990-Dec 2021), "Conference Proceedings Citation Index-Social Science & Humanities (CPCI-SSH)" (1980-Dec 2021), "Book Citation Index– Science (BKCI-S)" (2005-Dec 2021), "Book Citation Index–Social Sciences & Humanities (BKCI-SSH)" (2005-Dec 2021), and "Emerging Sources Citation Index (ESCI)" (2015-Dec 2021). The bibliometric analysis search was conducted on December 14, 2021.

3 Results and discussion

3.1 Descriptive analysis

The purpose of this study was to explore the literature on I4.0 in maritime studies. The study sought to identify current research trends, existing gaps, and main research directions based on the bibliometric results and a content analysis of the most important cited articles. A descriptive analysis of the trend of the publications both in terms of their frequency measures and types, most productive journals, the geography-based distribution of publications, and their subject categories could provide a broad picture of the current and future research directions, as explained below.

3.1.1 Trends of the publications

This section explores the trends of publications in terms of their frequency and types between 2011 and 2021. This analysis reveals the developmental trends and the current status of publications addressing Maritime 4.0. Figure 2 illustrates the distribution of the total publications (TP) from 2011 to December 2021. An initial search including I4.0 and maritime studies showed a total of 1428 publications written in English. The total publications per year rose from 37 in 2011 to 362 in 2021. The publications found appeared in eight different document types: articles (1284), reviews (49), early access (48), proceeding papers (34), editorial material (9), data papers (3), and retracted publication (1). Among all these types of documents, articles (90%), followed by reviews (0.03%), constituted the main body of the literature on the topic under investigation.

Figure 2 clarifies that research on I4.0 in maritime studies is a very recent phenomenon. The 11-year period can be further divided into two subperiods: (a) from 2011 to 2016, few publications addressed this topic; and (b) from 2016 to

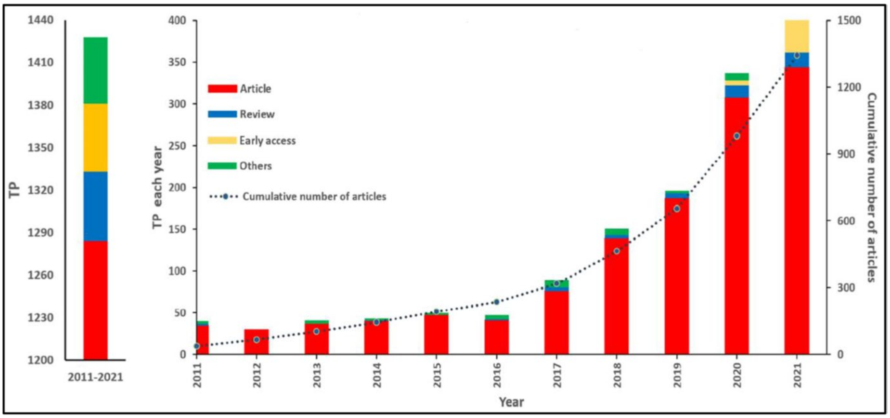

Fig. 2 Publication trends of Maritime 4.0 between 2011 and December 2021

2021, the number of publications showed a significantly increasing trend. Notably, the TP measure in 2021 (362) was about ten times greater than that in 2011 (37). Given this rising trend, one can expect to see a growing number of studies concerned with I4.0 in maritime studies in the next few years.

3.1.2 Most productive journals

This section distinguished the productive journals exploring Maritime 4.0 by computing the number of publications and the frequency of citations. This analysis would help researchers to easily trace journals that are most appropriate for publishing research on maritime 4.0. HistCite was used to analyze the most impactful journals. The data for this analysis was extracted from the WoS database. The HistCite-generated analysis results indicated that 413 journals published 1387 articles that addressed I4.0 in maritime studies. Most of them were prominent journals in the fields of ocean engineering, sustainability, marine science and engineering, transportation, and maritime policy and management. Table 2 provides an overview of the top 20 journals that published documents in relation to the topic under investigation. The top 20 most influential journals published 398 articles from 2011 to 2021, which roughly accounted for 32.7% of the TP. As Table 2 shows, the top 3 journals with the highest number of publications in the list were The Journal of Coastal Research, Ocean Engineering, and Sustainability, respectively.

The Journal of Coastal Research (with the highest TP measure: 77), Ocean Engineering (with the highest TGCS: 428), IEEE Internet of Things Journal (with the highest TLCS: 41 and the highest IF score: 12.3), and Maritime Policy and Management (with the highest TLCR measure: 40) were the four most productive journals that addressed I4.0 in maritime studies.

Table 2 The list of the top 20 journals ranked based on the number of publications. Total local citation score (TLCS) calculates the total number of times an article was cited by other articles in the collection. Total local citation score per year (TLCS/t) computes the average local citations received per year. Total global citation score (TGCS) represents the total number of times a journal was cited on the WoS database. Total global citation score per year (TGCS/t) shows the frequency of the annual citation based on the WoS data. Total local cited references (TLCR) is a measure of the number of cited papers in the sample under study. Finally, IF refers to the impact factor measure in 2021

Rank	Journals	TP	% of 1387	TLCS	TLCS/t	TGCS	TGCS/t	TLCR	IF	Country
1	Journal of Costal Research	77	5.6	2	0.5	146	27.6	2	0.8	US
2	Ocean Engineering	42	3	17	3.1	428	98.7	10	3.9	UK
3	Sustainability	39	2.8	0	0	204	58	31	3.6	Switzerland
4	Journal of Marine Science and Engineering	36	2.6	0	0	103	32.5	18	2.6	Switzerland
5	IEEE Internet of Things Journal	30	2.2	41	13.2	323	107.7	27	12	US
6	Remote Sensing	20	1.4	0	0	190	50.8	2	5.7	Switzerland
7	Maritime Policy and Management	16	1.2	23	6.77	122	28.9	40	3.7	UK
8	Polish Maritime Research	11	0.8	4	0.7	63	12.4	2	1.2	Poland
9	Journal of Navigation	10	0.7	4	0.42	97	10.9	1	2.7	UK
10	Transportation Research Record	10	0.7	2	0.25	47	6.3	1	1.8	US
11	Transportation Research Part E-Logistic and Transportation Review	9	0.6	20	4.92	207	61.8	10	7.1	UK
12	Journal of Intelligent & Fuzzy Systems	8	0.6	1	0.33	8	2.4	1	1.8	Netherland
13	Journal of Marine Science & Technology-Taiwan	8	0.6	2	0.53	10	2.6	3	0.7	Taiwan
14	Proceedings of the Institution of Mechanical Engineers, Part M	8	0.6	0	0	14	3.3	1	1.9	UK
15	Research in Transportation Business & Management	8	0.6	0	0	43	15.8	17	3.7	Netherland
16	Ships and Offshore Structures	8	0.6	0	0	52	8.9	1	2	UK
17	International Journal of Production Research	7	0.5	3	0.67	88	26.6	2	7.2	UK
18	Journal of Ship Production and Design	7	0.5	4	0.79	17	2.5	0	0.8	US
19	Marine Policy	7	0.5	0	0	34	10.8	2	3.9	UK
20	International Journal of Naval Architecture and Ocean Engineering	6	0.4	5	0.92	41	7.3	6	3.1	South Korea

3.1.3 Geographical distribution of the publications

By investigating the countries' collaboration network, it would be possible to identify international collaborations, potential collaborators, and the key countries that produced a large number of publications and majorly influenced research on Maritime 4.0. To evaluate the contribution of each country to the development of Maritime 4.0, a geographical distribution network of publications was drawn in CiteSpace. Figure 3 illustrates the collaboration network map of the countries. The network involves 94 nodes and 42 links generated from 2011 to 2021 based on 1-year slices. Each node represents a country or region; larger nodes would include a greater number of publications from the countries involved. A node with a high betweenness centrality (BC) measure (BC ≥ 0.1) was described as a *turning point* (Chen 2004) and was marked with a pink circle. Such countries collaborated more closely with the international nodes. The colors of the links between the nodes represent the first time a collaboration was established between two countries.

According to the information in Fig. 3, China (PRC), the USA, South Korea, England, Italy, and Spain, which exhibited larger node sizes, had a large number of publications concerned with I4.0 in the maritime industry. China (PRC), the USA, and Italy, which had purple inner circles, were the first countries engaged in this line of research back in 2011. The BC indicator helped to measure the importance of each node in the collaboration network. In the light of the BC measure, countries such as France, Egypt, Malaysia, and Finland extensively collaborated with most countries in this research field. In contrast, countries with a low BC measure would need to collaborate more with other countries or scientific institutions. Tables 3 and 4 provide more detailed information about the top 10 countries with the highest number of publications and about the BC measures from the cross-country collaboration network.

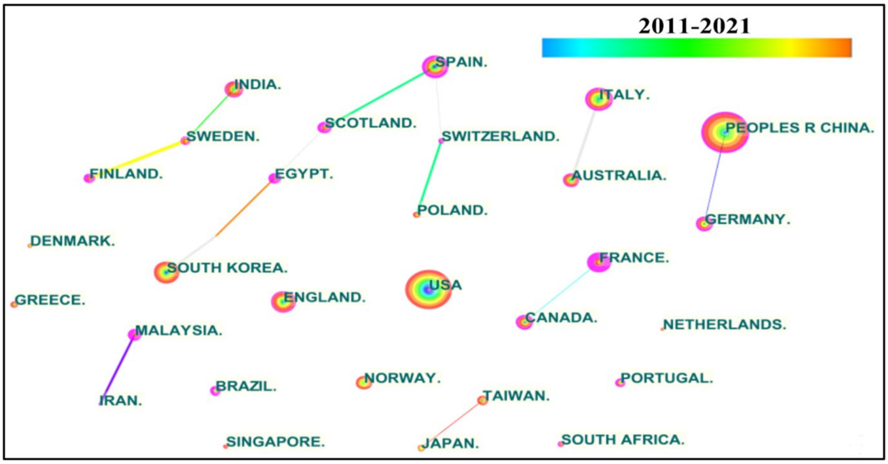

Fig. 3 The cross-country collaboration network (from 2011 to December 2021)

Table 3 The top 10 countries in the collaboration network (ranked based on the number of publications)

Rank	Countries	TP	BC	Rank	Countries	TP	BC
1	China (PRC)	369	0.4	6	Spain	63	0.52
2	USA	187	0.04	7	India	54	0.11
3	South Korea	90	0.00	8	Norway	53	0.00
4	England	86	0.11	9	Canada	49	0.22
5	Italy	81	0.25	10	Germany	48	0.34

Table 4 The BC measures and turning points in the cross-country collaboration network (ranked based on the BC measures)

Rank	Countries	BC	TP	Rank	Countries	BC	TP
1	France	1.13	34	6	Spain	0.52	63
2	Egypt	0.72	16	7	Brazil	0.43	16
3	Malaysia	0.7	19	8	China (PRC)	0.4	369
4	Finland	0.6	13	9	Switzerland	0.39	13
5	Scotland	0.58	27	10	Germany	0.34	48

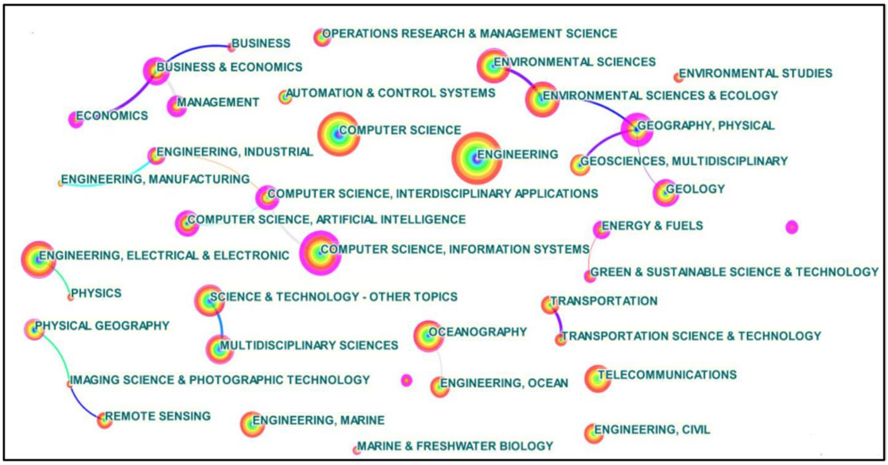

Fig. 4 The cooccurrence map of the subject categories in research on Maritime 4.0 between 2011 and 2021

3.1.4 Distribution of the publications based on their subject categories

Analyzing the distribution of the publications based on their subject categories could uncover the most significant topical issues over time (Hamidi and Ramavandi 2020). To address the priority of research topics in the realm of Maritime 4.0, a cooccurrence analysis of the subject categories was conducted in CiteSpace (see Fig. 4). The size of each node is proportional to the number of cooccurrences of the subject category. The line thickness represents the strength of the relationship between two categories. The

Table 5 The top 10 subject categories in the cooccurrence network of research on Maritime 4.0 between 2011 and 2021 (Year: refers to the year of publication as reported on the WoS database)

Rank	WoS subject categories	TP	Year	Rank	WoS subject categories	TP	Year
1	Engineering	600	2011	6	Oceanography	158	2011
2	Computer Science	436	2011	7	Science Technology	155	2011
3	Computer Science, Information System	338	2011	8	Engineering Marine	147	2011
4	Engineering, Electrical & Electronic	298	2011	9	Engineering Ocean	105	2011
5	Environmental Sciences & Ecology	251	2011	10	Transportation	103	2012

Table 6 The BC measures and the turning points of the cooccurrence network of the subject categories

Rank	WoS subject categories	BC	TP	Rank	WoS subject categories	BC	TP
1	Geography, Physical	1.40	103	6	Computer Science, Information Systems	0.91	338
2	Business & Economics	0.99	90	7	Geography	0.9	7
3	Management	0.95	58	8	Energy & Fuels	0.64	45
4	Computer Science, Interdisciplinary	0.93	56	9	Green & Sustainable Sciences	0.32	53
5	Economics	0.91	27	10	Operation Research & Management	0.18	78

colors of the lines show the first cooccurrence of the nodes. The nodes marked with pink circles represent the turning points in the network. The literature on Maritime 4.0 involved approximately 106 nodes (subject categories) and 51 links between 2011 and 2021. As shown in Fig. 4, research on Maritime 4.0 encompassed several disciplinary subject areas from various disciplines including engineering, computer science, environmental sciences, engineering, marine, transportation, business, and economic. These subject categories were grouped into 9 subject category clusters in CiteSpace.

In the network, the most predominant subject category was engineering as the largest node with 600 publications. Computer Science with a frequency of 436 publications was the second subject category. Table 5 lists the top 10 subject categories ranked by the number of publications. These categories accounted for most of the publications addressing Maritime 4.0.

BC measured the interrelationships among the nodes and could also indicate the interdisciplinarity of the scientific journals (Leydesdorff and Liu 2007). It was found that the category of Engineering was not only the most contributing category, but also it showed the highest BC measure (0.36) in the cooccurrence network of the subject categories. Table 6 displays the BC measures and the turning points of the cooccurrence network of the subject categories. As Table 6 shows, such categories as Geography, Physical, Business and Economics, and Management were, respectively, the turning points of the network and were strongly connected with the other categories. These turning points linked the studies dealing with different topics and could significantly affect the development of research on Maritime 4.0 (Zhang et al.

2020). In short, the cooccurrence analysis showed the interdisciplinary aspects of the literature on Maritime 4.0, which involved numerous disciplinary areas.

3.2 Cocitation network analysis

Cocitation analysis is an effective tool for mapping the intellectual structure of research areas, and it could be used to detect existing clusters of documents (White and Griffith 1981). Cocitation analysis has served as a standard measure of bibliometric analysis since the 1970s. It is defined as the frequency with which two documents are cited together (Small 1973). Moreover, cocitation provides a new method of exploring seminal works in a particular line of studies. Unlike bibliographic coupling, which provides a forward-looking perspective, cocitation pursues a retrospective approach (Belussi et al. 2019). Therefore, analyzing how documents are cited together can help researchers and practitioners to understand important past contributions in a scope of research (Trujillo and Long 2018).

Relying on cocitation analysis, this study created a network of document (reference) cocitations with 1114 nodes and 2219 links to identify key documents, research clusters, and the intellectual base. In the network, five main clusters were generated based on the log-likelihood ratio algorithm (LLR) in CiteSpace (see Fig. 5). A cluster represents a group of strongly connected articles in one specific research scope that has limited connections to articles in another research scope (Radicchi et al. 2004).

Modularity (Q) and the mean silhouette (S) are two important metrics that describe the overall structural properties of a network. The Q value falls between − 1

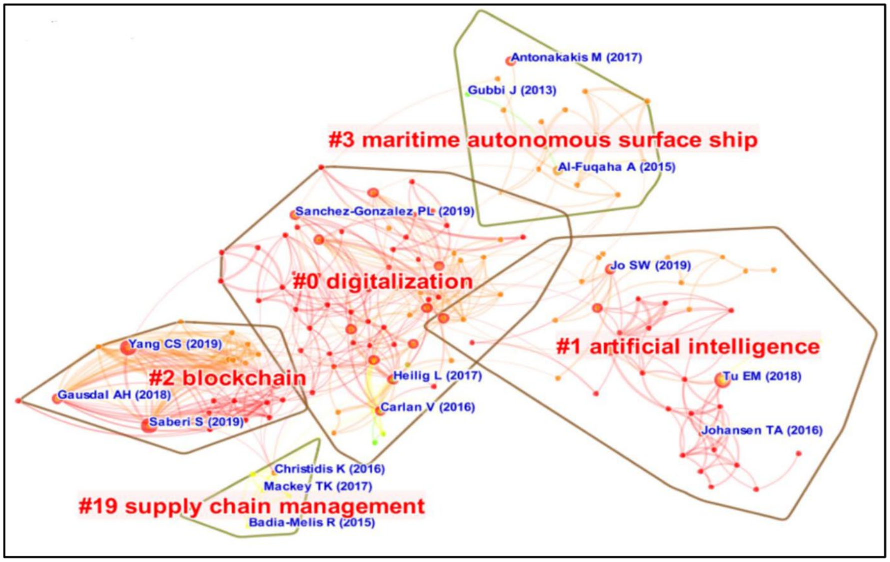

Fig. 5 A five-cluster view of the document cocitation network based on 1-year slices

and 1. Greater *Q* values indicate better clusters of nodes. A *Q* value falling between 0.4 and 0.8 would denote a significant structure division in cases *Q* is relatively high. The *S* value of a cluster falls between –1 and 1 and measures the quality of a clustered configuration. Larger S scores would indicate a higher degree of homogenization of nodes in a cluster. A value of *S* greater than 0.7 generally suggests that the cluster involves a high rate of credibility (Chen et al. 2014; Xu 2020). In this study, the cocitation network showed a *Q* value of 0.937, which indicated that the nodes were clearly defined within each cluster. The mean *S* score was 0.9284, which suggested a high degree of homogeneity of the nodes in the clusters. Table 7 more specifically reports the characteristics of these cocitation cluster. The data were extracted from CiteSpace based on the data collected from the WoS database.

Analyzing the important cited documents in each cluster offers a better understanding of the intellectual foundations and leading researchers in the research area under investigation. Table 8 lists the top 4 most significant cited documents in the five clusters.

As Fig. 5 and Table 7 show, the network was divided into five cocitation clusters. Below, the largest cluster (Cocitation Cluster # 0: Digitalization) is qualitatively analyzed. The largest cluster (#0), labeled "digitalization," had 72 members, accounting for 39% of total nodes in the network. The cluster's mean *S* value was 0.856, which showed a high degree of homogeneity. The mean year of publications in this cluster was 2018. The item with the highest burst rank in this cluster was Yang et al. (2018) with a burst value of 4.31, followed by Heilig et al. (2017) with a burst value of 4.05. The first article investigated the requirements and challenges those ports needed to address to implement the IoT.

In the case of citation counts, the top 3 items were Heilig and Voß (2017), Sanchez-Gonzalez et al. (2019), and Fruth and Teuteberg (2017), which showed citation counts of 120, 62, and 99, respectively. All these three cited publications (intellectual base articles) mainly focused on information systems (IS) and the digitalization of the maritime sector. Heilig and Voß (2017) offered a comprehensive overview of IS and information technologies (IT) applied in ports. The authors also extensively examined the functionality, standards, and the role of solutions regarding these two factors in port operations. *Digitalization* in Heilig and Voß's article referred to the administration of IS and IT. Global navigation satellite systems, electronic data interchange, radio-frequency identification (RFID), optical character recognition systems, and real-time location systems were samples of the key enabling technologies that could improve port operations. Examples of IS in seaports that were surveyed by the authors were the national single window, port community systems, vessel traffic services, terminal operating systems, and automated yard systems. Heilig et al. (2017) also provided an overview of the development and most recent digital transformations in modern seaports.

Sanchez-Gonzalez et al. (2019) used a systematic literature review, trying to gain a clearer understanding of most recent developments in relation to digitalization in maritime transport. Digital technologies in their study were categorized into eight domains: autonomous vehicles and robotics, AI, big data, virtual reality and augmented/mixed reality, the IoT, cloud and edge computing, digital security, and 3D printing and additive engineering. The authors also emphasized the strong

Table 7 An overview of the document cocitation clusters. The clusters were labeled based on the LLR algorithm provided in CiteSpace. "Size" denotes the number of members in a cluster. "Mean year" represents the average publication year of the documents in a cluster

Cluster number	Label (LLR)	Size	Silhouette value	From	To	Duration	Mean year	Activeness
# 0	Digitalization	72	0.856	2015	2020	5	2018	Active
# 1	Artificial intelligence	53	0.958	2014	2020	6	2017	Active
# 2	Blockchain	28	0.962	2015	2020	5	2018	Active
# 3	Maritime autonomous surface ship	21	0.984	2013	2020	7	2016	Active
#19	Supply chain management	9	0.993	2015	2018	3	2016	Inactive

Table 8 The list of the top 4 most active cited/citing documents in each cluster

Cluster no	Cited documents (intellectual-based papers)
# 0	(Heilig et al. 2017); (Sanchez-Gonzalez et al. 2019); (Carlan et al. 2016); (Fruth and Teuteberg 2017)
# 1	(Tu et al. 2017); (Jo et al. 2019); (Huang et al. 2020); (Johansen et al. 2016)
# 2	(Yang 2019); (Saberi et al. 2019); (Gausdal et al. 2018); (Bavassano et al. 2020)
# 3	(Al-Fuqaha et al. 2015); (Gubbi et al. 2013); (Stanić et al. 2018); (Kretschmann et al. 2017)
# 19	(Özyılmaz and Yurdakul 2017); (Toyoda et al. 2017); (Mackey and Nayyar 2017); (Abeyratne and Monfared 2016)

relationship between digitalization and I4.0 (Sanchez-Gonzalez et al. 2019). Fruth and Teuteberg (2017) carried out a systematic literature analysis to investigate the current state of digitization in maritime logistics (Fruth and Teuteberg 2017). One of the most cited studies in this cluster (Carlan et al. 2016) proposed a comprehensive framework to evaluate the costs and benefits of port community systems.

3.3 Keyword frequency analysis

Keywords represent key concepts addressed in a specific research area (Su and Lee 2010). Keyword frequency analysis, then, can help to reveal the focus of studies in a particular line of research. This study conducted a keyword frequency analysis of three periods in VOSviewer, namely, 2001–2010, 2011–2016, and 2017–2022, to substantially depict the hotspots of studies concerned with Maritime 4.0.

The minimum number of occurrences of a keyword was set at 3. Meanwhile, the keywords were screened and general or irrelevant ones were excluded. Next, the total frequency (TF) of the keywords in each period was calculated. The total frequency measure was the sum of the frequency of abbreviated, singular, plural, and synonymous keywords (e.g., IoT and Internet of things, strategy and strategies, autonomous ship and autonomous shipping, ship, and marine vehicle).

After the frequency of the keywords was measured, the keywords were clustered into five research themes: "digitalization technology," "methodology and techniques," "management," "safety and security," and "environmental issues." These clusters were identified in the light of the cocitation analysis results, content analysis, and an in-depth discussion. More specifically, in constituting the themes, the study investigated previous research on the topic, conducted in-depth discussions, found the similarities between the keywords, and relied on experts' judgments. Meanwhile, the clusters identified through the cocitation analysis (Fig. 5) further helped to group the keywords. As can be seen, the three clusters AI, blockchain, and autonomous ship represented aspects of digital technology associated with "digitalization technology" as the largest theme. As another cluster, supply chain management represented the keywords related to the "management" theme. Table 9 lists the frequently used keywords in research on Maritime 4.0 in three periods: 2001–2010, 2011–2016, and 2017–2022.

The current research topics and future research directions associated with each theme were identified in the light of cocitation analysis and keyword frequency

Table 9 Frequency measures of the keywords in research on I4.0 and maritime studies (2001–2022)

Themes	2001–2010		2011–2016		2017–2022	
	Keyword	TF	Keyword	TF	Keyword	TF
Digitalization technology	Neural networks	5	Simulation	18	IoT	182
	AI	5	AI	15	Automation	120
	Computer – simulation	5	Neural networks	15	AI	117
	Virtual reality	3	Cloud computing	8	Big data	116
			Geographic information system	9	Blockchain	88
			Big data	7	Machin learning	68
			Virtual reality	4	Neural networks	68
			IoT	4	Simulation	52
					Cloud computing	36
					Augmented reality	29
					Cyber physical system	21
					Autonomous ship	21
					IT	14
					IS	13
					port community system	8

Table 9 (continued)

Themes	2001–2010		2011–2016		2017–2022	
	Keyword	TF	Keyword	TF	Keyword	TF
Methodology and techniques	Genetic algorithm	3	Model	41	Model	183
			Optimization	19	Optimization	93
			Genetic algorithm	13	Risk assessment	33
			Digital elevation model	4	Mathematical model	15
			Evolutionary algorithm	3	Multicriteria decision-making	13
			Game theory	3	Case study	11
			Multicriteria decision-making	3	Time cerise	11
					Fuzzy logic	10
					Genetic algorithm	8
					Evolutionary algorithm	5

Table 9 (continued)

Themes	2001–2010		2011–2016		2017–2022	
	Keyword	TF	Keyword	TF	Keyword	TF
Management	System	4	System	32	System	174
			Prediction	20	Performance	99
			Performance	12	Supply chain	70
			Quality	4	Strategies	39
			Strategies	4	Innovation	37
			Efficiency	3	Knowledge	24
			Knowledge	3	COVID-19	23
			Monitoring	3	Monitoring	18
					Quality	18
					Efficiency	17
					Regulation	16
					Business model	15
					Value creation	4
					Standard	4
Safety & security	Collision avoidance	3	Risk	7	Security	59
			Security	5	Safety	51
					Collision avoidance	34
					Cyber security	27
					Risk	19

Table 9 (continued)

Themes	2001–2010		2011–2016		2017–2022	
	Keyword	TF	Keyword	TF	Keyword	TF
Environmental issues			Climate change	11	Sustainability	51
			Sustainability	6	Ship emission	32
			Robust	3	Energy efficiency	28
					Climate change	20
					Carbon emission	14
					Robustness	8
					Renewable energy	6
					Circular economy	3

analysis (as explained in more detail below). An in-depth literature review of the top 27 most cited documents also helped to formulate the future research directions in this field.

3.3.1 Digitalization technologies

This theme involved keywords representing I4.0 technologies in each generation digital transformation that occurred in seaports. Heilig et al. (2017) analyzed three generations, namely, paperless procedures, automated procedures, and smart procedures. The first generation (1980s) mostly focused on establishing basic IT infrastructure and software applications to support some terminal activities, such as port community systems governed by electronic data interchange. The second generation (1990s–2000s) supported the automation of terminal operations by integrating terminal equipment and vehicles (e.g., automated guided vehicles and automated stacking cranes) and IT-regulated terminal infrastructure. The ongoing third generation of digital transformation (2010s-present) has concentrated on managing port operations and terminal infrastructure by adopting smart technologies (e.g., sensors and actuators). The current research topics and future research directions addressing I4.0 technologies in relation to these three generations are explained in more detail below.

As Table 9 shows, researchers are presently more concerned with the third generation (i.e., I4.0) and the second generation (i.e., automation) of digitalization technologies than the first generation. For instance, in the third period (2016–2022), researchers did not concentrate much on topics associated with the first digital generation (e.g., the structure of IT as in electronic data interchange) or IS (e.g., port community systems). The frequency of "automation" as a keyword, which was a representative of the second digital generation, revealed that researchers were still concerned with the technologies of this generation including automatic identification systems, RFID, and automated guided vehicles. I4.0 technologies were the emerging topics in research on Maritime 4.0. Among the topics, the keyword "IoT" showed the highest frequency (182). The frequent occurrences of such keywords as "IoT," "artificial intelligence," "big data," "blockchain," "cloud computing," and "augmented reality" revealed that researchers remarkably focused on these I4.0 technologies in maritime studies.

However, the application of I4.0 technologies in the maritime industry will need studies to further investigate some areas. For instance, although IoT and blockchain constituted the main research trends exploring maritime 4.0, there are emerging paradigms left unaddressed in the existing studies. The main research gaps in relation to IoT are the Internet of services (IoS), the Internet of content (IoC), the Internet of people (IoP), and the Internet of agents (IoA). Similarly, other generations of blockchain (e.g., Bitcoin and Ethereum) were left unexplored in the existing studies.

Among other I4.0 technologies as shown in Table 9, "autonomous ship" and "cyber-physical system" showed a low frequency of 21. Meanwhile, no keywords were found in relation to "3D printing" in maritime studies. A content analysis of the publications addressing Maritime 4.0 also revealed that "3D printing technology" was only mentioned in two studies (Chen 2017; Kostidi and Nikitakos 2018). There are, of course, other areas to be explored. Sanchez-Gonzalez et al. (2019) observed that cloud computing, 3D printing, and additive manufacturing in shipbuilding and seaports were the domains that required more research. In addition, they concluded that future research would have to explore the applications of big data in ship design and shipbuilding, the functions of virtual/augmented reality in seaports, and the uses of robotics in sea transport services. De la Peña Zarzuelo et al. (2020) pointed out that although IoT and sensing solutions were the leading topics in other emerging technologies, other domains of maritime studies were relatively underappreciated such as blockchain, 3D printing, augmented reality, big data, and AI.

3.3.2 Methodology and techniques

The research on Maritime 4.0 has drawn on different research methods that can serve various research goals. In this study, the research methods in the literature on Maritime 4.0 were divided into two categories: classical computing techniques and soft computing techniques. The former would use mathematical models and algorithms, whereas the latter would draw on AI technologies including neural networks, fuzzy logic, and evolutionary algorithm expert systems (Statheros et al. 2008). Comparing the frequency of the keywords over the periods under investigation demonstrated that "model" (183), "optimization" (93), "risk assessment" (33), and "mathematical model" (15) were, respectively, the emerging topics in relation to "methodology and techniques" in the literature on Maritime 4.0. Furthermore, "multicriteria decision-making" and "case study" were also important topics.

In addition to classical techniques that relied on mathematical models, the frequent occurrences of such phrases as "fuzzy logic" and "evolutionary algorithm" suggested that researchers also focused on soft-computing techniques. For instance, from the perspective of methodological applications, Statheros et al. (2008) identified two autonomous ship navigation methods in the studies: (a) classical techniques regulated by mathematical models and algorithms and (b) soft-computing techniques governed by AI. Furthermore, Kretschmann et al. (2017) analyzed the economic benefits of unmanned autonomous ships, comparing them with a conventional vessel.

Yet, further research should quantify the impact of I4.0 technologies on the maritime industry. For instance, research can measure the performance improvement of seaports' business processes via IoT technologies (Ferretti and Schiavone 2016). Furthermore, Heilig et al. (2017) emphasized the application of the game theoretic framework, asserting that future studies should investigate the economic impact of digitalization on the maritime industry.

Zhang and Lam (2019) explained that future studies should employ causal models, such as structural equation modeling, to analyze the dynamics of technology adoption barriers. De la Peña Zarzuelo et al. (2020) argued that future research should conduct a cross-referenced survey describing how I4.0 technologies are embedded in different port functions such as services to ship and merchandize services. To enhance blockchain implementation, researchers can conduct case studies and pilot programs. Future research should also evaluate post-implementation success/failure factors of I4.0 technologies (Saberi et al. 2019). Developing new fuzzy models and hybrid models (e.g., game theory and genetic algorithms) can also serve as interesting topics for future research.

3.3.3 Management

The theme of "management" included current research topics, gaps, and future research directions in the literature on Maritime 4.0, by focusing on managerial issues. The main concerns in this theme were systematic perspective, monitoring and performance measuring, efficiency and innovation, regulatory frameworks, business models, design, and related standards. According to Table 9, keywords such as "system," "performance," "supply chain," "strategies," "innovation," "monitoring," "quality," and "efficiency" were the most frequent keywords related to the theme of "management." This observation suggested that the adoption of I4.0 could become a requirement for value chain activities that maritime organizations undertake. For instance, the frequency of "system" showed a rapid increase from 4 occurrences in the 2001–2010 period to 174 ones in the 2017–2022 period. This remarkable increase indicated that the systematic approach to Maritime 4.0 could be the focus of future research. In the same vein, Saberi et al. (2019) recommended that further research should focus on system-related issues of blockchain technology that can limit its adoption (Saberi et al. 2019).

Furthermore, the increase in the frequency of "quality" showed that researchers focused on the impacts of adopting I4.0 on improving quality in the maritime industry. The increase in the frequency of "efficiency" also revealed the importance of efficiency improvement as the main goals of I4.0, Port 4.0, and Maritime 4.0 (Jahn and Saxe 2017). In addition, "innovation" with a frequency of 37 was an emerging keyword, which signified the role of digitalization and I4.0 as the main drivers of innovation. Some scholars (e.g., Carlan et al. 2016) addressed digital innovation in the maritime industry.

Emerging keywords such as "regulation," "business model," "value creation," and "standard" less frequently appeared in the literature on Maritime 4.0. Of course, these underexplored areas could inspire future research. Among these, however, regulatory uncertainty seems to be the greatest concern in the maritime industry. For instance, from a legal perceptive, a regulatory framework should formulate the applications of I4.0 technologies in the maritime industry. For example, Lehmacher and McWaters (2017) argued that regulatory governance (i.e., agreements, laws, and practices) may be the most challenging obstacle to the implementation of blockchains. This issue can serve as an interesting future research topic. Fruth and Teuteberg (2017) recommended that I4.0 applications in the future should comply with stricter environmental requirements. Similarly, Heilig and Voß (2017) underscored the incorporation of legacy systems and enabling technologies. Investigations should also identify the drivers of and barriers to transparency and trust in the maritime industry (Munim et al. 2020).

Probing into business models, Chan (2015) argued that the impacts of AI and machine learning on business models could inspire future research (Chan 2015). In relation to digital standards, one can refer to the research of Schleyerbach and Mulder

(2021), who examined various digitalization and standardization achievements of the digital container shipping association as an industry-based standards organization dealing with digital transformation. As far as standardization is concerned, developing consistent technical standards for blockchain technology can contribute to future improvements (Yang 2019). More studies should also explore the contributions and applications of knowledge, resources, and competences involved in processes of value creation while unfolding the dynamics of IoT-based business models (Metallo et al. 2018).

3.3.4 Security and safety

Although I4.0 brings about advantages, it also involves some security and safety risks that should be taken into consideration. The growing availability of data (such as data provided by automatic identification systems), the importance of mobility in logistics, and information exchange are some of the factors that highlight the urgency of higher levels of data security and data protection. As such, organizations must endeavor to prevent sensitive systems from being manipulated. Current research topics/gaps and future research directions of I4.0 technologies in the maritime industry are further explained below.

"Security" was the keyword with the highest frequency in the theme of "security and safety." In the period under investigation (2001–2022), the frequency of keywords such as "security" and "collision avoidance" showed an increase from 2017. As an emerging keyword, "cyber security" is concerned with issues of security and privacy in I4.0 implementation, which are currently potential concerns in the maritime industry. Some studies focused on the application of AI in improving security in shipping (Wen et al. 2012), security assessment of RFID systems in IoT applications (Fernández-Caramés et al. 2016), and security requirements of autonomous ships (Kavallieratos et al. 2020). Lee and Park (2017), however, stated research on the security of maritime cloud computing remained underdeveloped. Furthermore, the problem of cyberattacks would demand further exploration (Fruth and Teuteberg 2017). Sanchez-Gonzalez et al. (2019) pointed out that digital security in shipbuilding and seaports was not the subject of any formal investigation.

Future research should revisit blockchain privacy/security risks, trying to minimize them (Green et al. 2020). Ahokas et al. (2017) concluded that cybersecurity was not currently included in the International Maritime Organization's port safety and security conventions such as international ship and port facility (ISPS) code or international safety management (ISM) code. Therefore, future studies should find ways of mitigating ports' exposure to cyberthreats. Investigating risk, Kretschmann et al. (2017) concluded that future research should offer a clearer understanding of risks associated with higher degrees of autonomy in shipping. In addition to studies dealing with security and privacy, research should also address safety-related concerns in the implementation of I4.0 technologies, especially autonomous ships. Safety will be the most interesting and important aspect of autonomous ships (Ahvenjärvi 2016). Therefore, future research should explore the development of security and safety systems that can handle data security and data protection while dealing with data misuse and cyberattacks.

3.3.5 Environmental issues

Environmental issues can challenge the maritime industry. The adoption of the UN's 2030 Agenda for Sustainable Development and the ambitious objective of the International Maritime Organization to decarbonize the sector by 2050 have prompted researchers to inspect shipping companies' activities/policies and their responses to the requirements of sustainable development (Di Vaio et al. 2021). I4.0 technologies represent a possible solution that can impact the environmental dimension of sustainability in the maritime industry. This section addresses the current research streams and future research trends concerned with maritime environmental issues in the light of I4.0.

As Table 9 shows, the most important emerging topics in the environmental theme of research on Maritime 4.0 included "sustainability," "ship emission," "energy efficiency," "climate change," and "carbon emission." "Sustainability," of course, was the most frequent keyword. This suggested that sustainability functioned as an umbrella concept that covered various sustainability-related concerns such as recycling, waste minimization, cleaner production, zero-emission, zero-growth economy, green economy, triple bottom line, life-cycle assessment, sustainable consumption, corporate social responsibility, blue economy, shared value creation, industrial ecology, and circular economy (D'Amato et al. 2017).

Exploring sustainability, Di Vaio and Varriale (2019) emphasized the importance of analyzing the link between I4.0, environmental sustainability, and accounting, by studying specific observations in the port industry. Strandhagen et al. (2020) and Ramirez-Peña et al. (2020) explored the impact of I4.0 technologies on sustainable shipbuilding. Similarly, Del Giudice et al. (2022) highlighted the importance of harnessing the role of digitalization and new technologies in integrating sustainability into seaports' corporate strategy.

Keyword frequency measures in Table 9 show that, along with the focus on sustainability in research on Maritime 4.0, only circular economy (as a movement of sustainability), renewable energy (as a circular economy strategy), and ship emission and carbon emission (as zero-emission measures) received increasing attention as topical concerns. A few studies have addressed the link between circular economy and the maritime industry (Okorie et al. 2018; Rosa et al. 2020). Meanwhile, only Jensen et al. (2021) probed into the integration of circular economy in Maritime 4.0. They constructed a digital framework that could reinforce maritime circular economy.

Fletcher et al. (2018) employed several machine learning algorithms to estimate shipping emissions (Fletcher et al. 2018). The frequency of "energy efficiency" as a keyword (see Table 9) indicated the importance of this concept as one of the foundations of smart ports (De la Peña Zarzuelo et al. 2020). Future research should also view Maritime 4.0 from the perspective of industrial symbiosis and social responsibility. Considering these issues, the study proposes a research framework guiding future research directions addressing Maritime 4.0 (see Fig. 6). The five themes identified link the current research topics with future research directions (see below for further explanation).

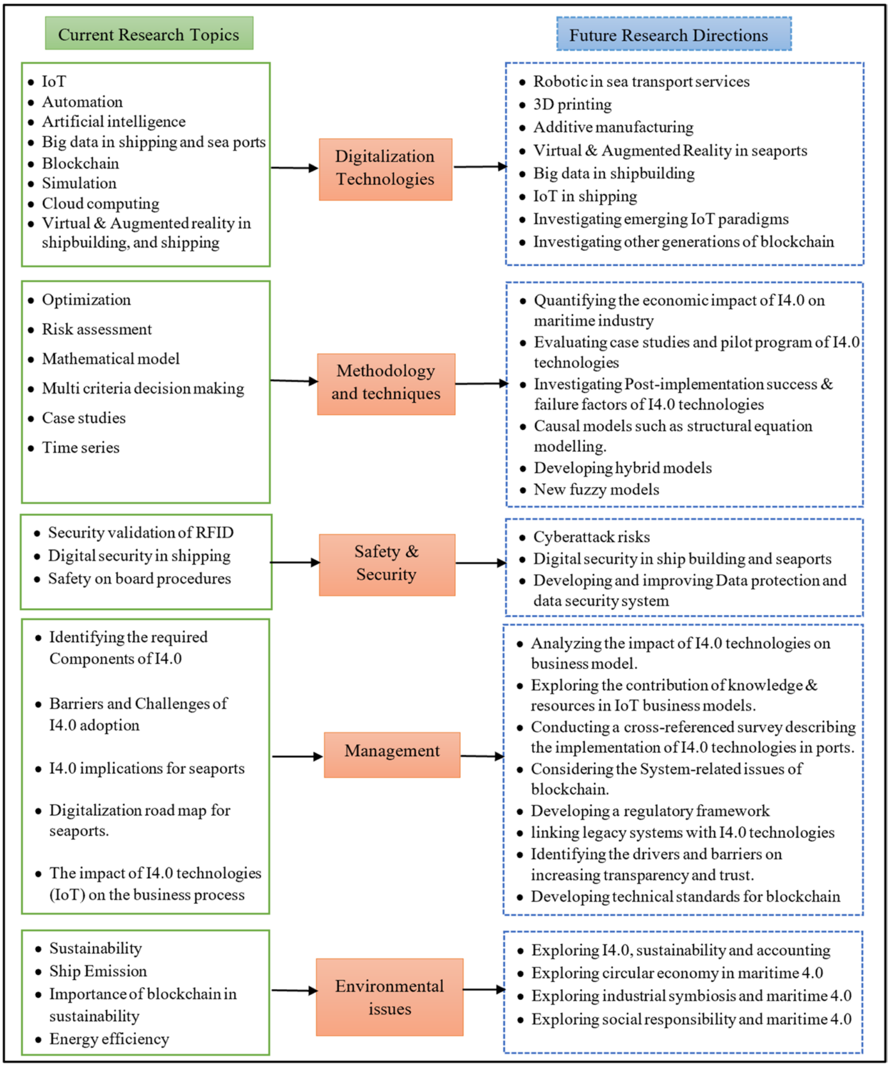

Fig. 6 Future directions research exploring Maritime 4.0

4 Results

This study conducted a bibliometric analysis of the literature on Maritime 4.0 to identify recent emerging topics, gaps, and future research directions in this area of research. More specifically, the bibliometric analysis focused on the citations (publication distribution, productive journals, and collaborations between countries), cooccurrence of subject categories, cocitation analysis, and keyword frequency analysis. The main findings of the study are reported below.

1. The results of analyzing the publication trends (Fig. 2) revealed that the number of publications exploring Maritime 4.0 underwent a significant increase from 2011 and could continue to grow rapidly in the next few years. The graph of the development of field showed two distinct periods: from 2011 to 2016 and from 2016 to 2021 which marked the most productive period of research on this field.
2. The analysis of the statistics processed in CiteSpace and HistCite showed prominent academic journals had published research on Maritime 4.0. In terms of the number of publications, the top three productive journals in this area of research were The Journal of Coastal Research, Ocean Engineering, and Sustainability, respectively.
3. The geographical distribution of the publications revealed that China (PRC), the USA, and Italy were the leading countries in studies concerned with Maritime 4.0. Analyzing collaborations across countries clarified that France had the highest rate of collaboration with other countries.
4. Investigating the distribution of the publications in terms of subject categories showed that the topics were strongly associated with engineering, followed by computer science, environmental sciences, and ecology.
5. A document cocitation analysis was conducted to detect research clusters, key publications, and intellectual bases. It was found that Khan et al. (2018) from Cluster #19, followed by Saberi et al. (2019) from Cluster #2, were the most cited authors in the network. Based on these results, there were five major research clusters that illustrated the historical evolution of research on Maritime 4.0 studies: digitalization, AI, blockchain, maritime autonomous surface ships, and supply chain management. The findings also revealed that Cluster #0 was the largest and most active area of research, whereas Cluster #19 was the smallest spot in the network.
6. Keyword frequency analysis demonstrated that the research hotspots stemmed from five themes: digitalization technology, methodology and techniques, management, safety and security, and environmental issues. The keyword frequency analysis of the literature revealed that, after 2016, researchers started to focus more on the third and second digital generations (I4.0 technologies and automation) than the first digital generation (IS and IT). The most extensively studied I4.0 technologies in the maritime industry were IoT, AI, and big data, respectively. Meanwhile, 3D printing remained an underdeveloped topic, although it deserves further research. Recent studies addressed such subjects as the security and sustainability of Maritime 4.0. The most popular subjects in the theme of methodology and management were optimization, system, and performance.
7. In the light of the results of the bibliometric analysis and an in-depth literature review, the study proposed future research directions for each of the five themes identified, and it clarified how they could be linked to the existing research topics.

Finally, it should be emphasized that today's maritime industry is transitioning into the highly digitalized industrial paradigm that I4.0 seeks to achieve. However, despite increasing research on I4.0 in the maritime industry, Maritime 4.0 represents an underdeveloped topic that requires extensive research. In particular, its involvement in environmental issues (e.g., circular economy and shared value creation) in the maritime industry remains insubstantial. From a managerial perspective, it would be necessary to explore the contributions of I4.0 technologies to monitoring, tracking, and controlling ships and cargo movement. In addition, it would be important to implement new digitized business models and develop consistent standards for the implementation of I4.0 technologies. On the other hand, digital security seems to be the main challenge in the maritime industry. As such, researchers should explore essential security and safety measures while implementing I4.0 technologies in this industry.

The study suggested some implications for business managers and academic researchers. Maritime companies should evaluate their digitalization level, explore I4.0 technologies compatible with their structures and services they offer to ship/cargo owners, and move toward Maritime 4.0 to maximize their value retention. The findings can help researchers readily orient themselves to the findings in the literature and easily understand the frontiers of research on I4.0 technologies and the maritime industry. Furthermore, the findings can serve as a reference for researchers to gain awareness of the current status of research, the existing gaps, and future research trends in the field of Maritime 4.0. For instance, the findings offer valuable insight into the current and future research methods and techniques and the contribution of each digital technology. Scholars must further explore underdeveloped I4.0 technologies in relation to environmental, methodological, managerial, and security issues in the maritime industry.

Declarations

Conflict of interest The authors declare no competing interests.

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