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Knowledge Mapping Analysis of Intelligent Ports: Research Facing Global Value Chain Challenges

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Abstract: Integrated technology management in building smart ports or intelligent ports is a crucial concern for global sustainable development, especially when human societies are facing increasing risks from climate change, sea-levels rising, and supply chain disruptions. By mapping the knowledge base of 103 papers on intelligent ports, retrieved in late December 2022 from the Web of Science, this study conducted a roadmapping exercise using knowledge mapping findings, assisted by Bibliometrix, VoSviewer, and customized Python scripts. The three structural (intellectual, social, and conceptual) aspects of knowledge structure reveal the significance of the internet of things (IoT), the fourth industrial revolution (Industry 4.0), digitalization and supply chains, and the need for digital transformation alignment across various stakeholders with Industry 4.0 practices. Furthermore, an even geographical distribution and institutional representation was observed across major continents. The results of the analysis of the conceptual structure demonstrated the existence of several established and emerging clusters of research, namely (1) industry data, IoT, and ICT, (2) industry 4.0, (3) smart airports, (4) automation; and (5) protocol and security. The overall empirical findings revealed the underlying technology and innovation management issues of digital transformation alignment across stakeholders in IoT, Industry 4.0, 5G, Big Data, and AI integrated solutions. In relation to roadmapping, this study proposed a socio-technical transition framework for prototyping ecosystem innovations surrounding smart sustainable ports, focusing on contributing to valuable carbon or greenhouse gas emission data governance, management, and services in global value chains.

Keywords: system innovations; sustainable smart ports; strategic foresight; intelligent ports; global value chains; digital transformation; business eco-systems; minimum viable ecosystems; socio-technical transitions

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1. Introduction

Roadmapping can be a valuable strategic tool for research and innovation management [1,2], especially for complex issues, such as climate change and carbon emission reduction [3]. Port development and management, including port logistics [4], can also use roadmapping to explore how digital technologies can advance the smart and sustainable development of ports, port cities, and global value chains. The "greening" of global value chains or global trade [5], including embedding environmental, social and governance (ESG) reporting practices and data, can begin with the "greening" of ports, as evidenced by the industrial agenda for the World Port Sustainability Program (WPSP) [6]. Indeed, ports need to improve their environmental performance, while not losing their competitiveness. The WPSP has exemplified the contribution by a major sector in the supply chain to the UN Sustainable Development Goals (SDGs), aligning the industry best practices and sustainable development actions, especially with the targets of SDG 9, 14 and 15 [7], including the knowledge of key actors and driving factors. Similarly, the United Nations Conference on Trade and Development (UNCTAD) Framework for Sustainable Freight Transport also provides a methodology and tools to support step-by-step decision-making processes for sustainable operations [8]. Roadmapping for stakeholder alignment in smart ports from the supply chain perspective is, thus, necessary.

The roadmapping technology of sustainable smart ports is also important as it faces challenges in the supply chain instability caused by the COVID-19 pandemic [9] and geopolitical tensions [10]. In fact, it points to the need to foster service transformation using digital technologies [11,12]. For instance, ports can provide sustainable smart services that advance the resilience and reliability of supply chains. Moreover, roadmapping points to the need for an advanced supply-chain performance evaluation. For instance, a bibliometric analysis of the performance evaluation for supply chain disruption highlighted the notion of reconfigurability [13]; thus, sustainable smart ports can provide reconfigurable services that tackle disruptions. When facing the risk from climate change, sea-levels rising, and supply chain disruptions, ports and companies can collaborate by adopting digital transformation to improve performance and competitiveness [14], and by identifying pathways to ensure supply chain resilience [15–17]. Sustainable smart ports should contribute to a more reliable and resilient supply chain. The shared interests in supply chain sustainability provide common grounds for experts and professionals, coming from port management and supply chain management, to work on a roadmap for the application scenario of smart ports that applies information communication technologies (ICTs), including artificial intelligence (AI) and the internet of things (IoT).

In practice, Finnish smart and green port ecosystems are an example of the ongoing development of sustainable smart ports, as demonstrated in a 2022 brochure [18]. Offered in this brochure are solutions for the following aspects: (1) port design; (2) network infrastructure, connectivity, and data management; (3) digital platforms; (4) software applications; (5) autonomous systems; (6) automated and precisely tracked cargo and passenger flows; and (7) energy infrastructure, new fuels, marine maintenance, and environmental solutions. Furthermore, as the top port with the highest container throughput in 12 consecutive years, the Shanghai International Shipping Center celebrated its achievements in green transformation, digital intelligence, and robust resilience [19]. In synthesis, smart and green port development matters for digital supply chains.

1.1. Typical Roadmapping Questions

Drawing on roadmapping practices and research for technology and innovation management [20–28], common roadmapping questions can be asked to identify and plan for future opportunities and challenges in sustainable smart ports, as follows:

1. What resources are needed to achieve carbon neutrality goals and sustainable development objectives?
2. What are the current and emerging technologies? How will they impact the business models in the short term and in the long term?
3. What collaborations, and which stakeholders, are necessary to bring innovative ideas to market?
4. What are the key trends and disruptions? What are the potential opportunities and threats?
5. How might we leverage technologies to solve problems by designing new products, services, or business models?

As any roadmapping exercise requires definitions of its scope, purpose, and industry, this study aimed to explore the aspect of integrated technology management or integrative solutions for intelligent ports facing the risks of climate change, sea-level rise, and supply chain disruptions. Assuming that ESG and carbon emission data as primary resources (thus answering roadmapping question #1), and that digital technologies will have substantial short-term and long-term impacts (thus answering roadmapping question #2), this study aimed to answer remaining questions #3–#5.

1.2. A Roadmapping Question for Ecosystem Innovations

Given its focus on the ESG and carbon emission data as primary resources, this study aimed to explore a range of new products, services, or business models surrounding these data resources, which can be seen as types of ecosystem innovation. The concept of ecosystem innovation has expanded the practices of prototyping minimum viable products (MVPs) towards those of minimum viable ecosystems (MVEs) for scaling business model success [29]. Thus, while intelligent ports can be seen as MVPs to solve current sustainability problems of modern ports, global supply chains can be seen as potential MVEs where intelligent ports introduce and embed sustainability practices and data into an ecosystem, including various supply chain business models and operations that can be connected, networked, and coordinated.

An integrated roadmapping question can thus be proposed as follows: How might we leverage digital technologies, especially using ESG and carbon emission data, to solve the problems of various stakeholders of intelligent ports, based on the empirical understanding of the key trends, opportunities, and threats? Seen from the viewpoint of business models for MVEs, in the abovementioned Finnish and Chinese examples, various innovative actors have started to provide values in areas, such as digital and electrified infrastructure, 5G and IoT connectivity, smart shipping, port digitalization, terminal automation, port and cargo automation, smart ships, and port consulting and training. Hence, a survey of technology solutions and knowledge inquiries is thus needed for integrated roadmapping.

1.3. Knowledge Mapping Questions for Integrated Roadmapping

Technology solutions are expected to be integrated into the socio-technical arrangement of port operations with the potential to facilitate everyday operations, predict future investment areas, anticipate maintenance needs, and respond to emergencies. In this way, they are expected to empower actors in the port business ecosystems, engaging stakeholders toward resilient, sustainable, and smart ports. In addition, they should also enhance the relationship between ports on the one hand, and port cities, global trades, and global value chains on the other. Indeed, digital platform companies are reshaping the geography of logistics. For instance, Alibaba's new airport hub in Belgium has raised issues regarding its positive and negative impacts on the local and European communities [30], which illustrates the importance of dialogues and collaboration across stakeholders to generate sustainable win-win solutions. Ecosystem innovations are, thus, needed to ensure positive impacts at various levels and across multiple stakeholders, especially for seaports and airports which are essentially complex systems themselves, and together constitute a complex supply chain network system at the global level.

The complexity of developing intelligent ports requires knowledge mapping regarding the twin green and digital transition towards sustainability [31,32], so as to provide a roadmap including viable pathways for positive development. Indeed, both seaports and airports need to contribute to carbon neutrality and sustainable development goals. They constitute essential nodes that make global transportation, global trade, and global supply chains possible. They are expected to become zero-emission, and also bring positive impacts when serving their customers and interacting with their service providers. Previous research examined the requirements for sustainable smart ports. For instance, a review of the energy and infrastructure of green seaports examined technological solutions, including electrification, power supply, and energy storage systems [33]. Furthermore, an Industry 4.0 review was conducted for the port and maritime industry [34]. Nonetheless, to the best of the authors' knowledge, there is currently no systematic review of intelligent ports that can support roadmapping efforts. Such a mapping of current knowledge is needed for the twin green and digital transition of global supply chains.

With the purpose to provide strategic foresight for ecosystem innovations, this study conducted a knowledge mapping analysis of the latest literature. The specific mapping questions are outlined as follows:

1. What are the intellectual, social, and conceptual structures of current knowledge, including specific information and relational patterns on the main authors, institutions, concepts, etc.?
2. What are the socio-technical arrangements among the various stakeholders of intelligent ports?
3. What are the specific key trends, opportunities, and threats?

The findings of this study are expected to contribute to a socio-technical transition framework for ecosystem innovations. The resulting framework is expected to contextualize the evolution of multiple radical niche innovations (e.g., digital technologies, such as AI) challenging incumbent systems (e.g., high-pollution infrastructures or behaviors) at multiple levels [35–37], thereby answering the main roadmapping question.

2. Materials and Methods

To provide evidence for roadmapping, this study conducted knowledge mapping based on bibliometric data, following bibliometric-based science and technology mapping conventions [38–40]. Knowledge mapping allows researchers to produce structured visualization and analysis outcomes to support roadmapping, which in turn provides structured strategic planning for ecosystem innovations.

2.1. Knowledge Mapping

Knowledge mapping, or science mapping [41], provides visualizations of knowledge in a structured fashion. The research materials employed in this study come from the Web of Science Database and include the following citation indices: Science Citation Index Expanded (SCI-EXPANDED); Social Sciences Citation Index (SSCI); Arts & Humanities Citation Index (A&HCI); Conference Proceedings Citation Index—Science (CPCI-S); Conference Proceedings Citation Index—Social Science & Humanities (CPCI-SSH); and Emerging Sources Citation Index (ESCI). Table 1 shows the basic information of the resulting dataset, which includes 103 bibliometric records retrieved in late December 2022, covering a time span from 2013 to 2023.

Table 1. Dataset basic information.

Bibliographic Data Source	Web of Science Core Collection
Search query	TS = (((“smart port?”) OR (“ intelligent port?”)) OR ((“smart seaport?”) OR (“intelligent seaport?”)) OR ((“smart airport?”) OR (“intelligent airport?”)))
Timespan	2013–2023
Sources [1]	76
Documents	103
References	3960
Average citations per document	7.485
Author’s keywords (DE)	361
Keywords plus (ID)	150
Authors	346
Authors—co-authors per doc	3.87
Types—article	63
Types—proceedings paper	35
Types—review	5

[1] Including journals, conferences, books, etc.

Knowledge mapping often uses bibliometric analysis and visualization tools to show knowledge bases [42] or research fronts [43]. To illustrate how bibliometric information can constitute different aspects of knowledge base mapping, this paragraph describes how keywords can be systematically analyzed and visualized for mapping. As shown in Table 1, a search query was defined to gather the literature based on keywords, such as intelligent ports and smart ports. There were 361 distinct values of authors’ keywords (DE) in the collected dataset, providing one dimension of the knowledge base for mapping. Following the best practices of bibliometric analysis, Python scripts and experts' coding were deployed to clean the data and ensure a consistent representation of the main keywords. For instance, both terms "airport" and "airports" were transformed into the same term "airports." The, software applications, such as Bibliometrix [44] and VOSviewer [45,46] were then employed.

Similarly, other bibliometric data, such as authors, affiliations, references, and the relationship among them (e.g., co-word, co-authorship, and bibliographic coupling) can be systematically analyzed and visualized. In this way, knowledge mapping can be employed to produce visualization and analysis outcomes to support horizon scanning [47–49] or roadmapping [20,49], as discussed in the following sub-sections.

2.2. Roadmapping: Ecosystem Innovations Concerning ESG and Carbon Emission Data

Roadmapping supports technology and strategic planning in a structured manner [21], thus offering an instrument to summarize the current status in support of technology assessment and forecasting [50]. Roadmapping can also help by turning visions into actions, as evidenced by climate change adaption roadmaps [1]. As a method of future studies, the roadmapping exercise has two main advantages [20]. First, the visual feature of roadmapping provides an overall picture that supports strategic communication and enables cross-sector multi-stakeholder dialogue. These visual and strategic communication outcomes are critical to build consensus and action plans. Second, the time-based framework of roadmapping can be instructive in the integration, alignment, and synchronization of critical information, methods, and tools. These integration and alignment efforts facilitate a more systematic discussion of the time dimension of change, transition, transformation, and ecosystem innovation. Roadmapping should be used to formulate and test strategies and policies by defining the scope and focus, critical data alignment, and scaling ecosystem innovation for sustainable growth. Therefore, the roadmapping [20,49] exercise constitutes a strategic management effort based on the analysis of technology and business potential, while at the same time avoiding the limited views and biases of expert opinions [50].

A technology roadmap for intelligent ports is expected to deliver the usefulness of the ESG and carbon neutrality management and services in envisioning the future of intelligent ports, especially for networked collaboration [2], transparency, and complexity. In recent years, the methods and tools of roadmapping have evolved from physical tools, such as paper charts and sticky notes to digital tools, such as interactive displays and whiteboard software [23,51]. Accordingly, this study used the online whiteboard service, Miro.

To explore viable technology management pathways for intelligent port development in the "greening" of global value chains, especially concerning the ESG and carbon emission information that they can provide, the knowledge mapping outcomes must be discussed to identify opportunities for collaboration and alignment. The knowledge base generated was, therefore, used to inform the concluding parts of this study, which aimed to explore the interconnection and interoperability potential of both physical and cyber aspects of smart ports that encourage open collaboration and ecosystem innovations. These possibilities can be advanced by focusing on the ESG and carbon neutrality management and services [16,52–56] that can be provided by smart ports, at the different levels of constituting components, devices, networks, systems, or applications. In short, the bibliometric findings are expected to contribute to indicate how ecosystem innovations can advance the socio-technical transitions toward sustainability, especially with the possibilities of digital tools and technologies.

3. Results

This section first describes the bibliometric findings covering the intellectual, social, and conceptual structure of the current knowledge based on relational bibliometrics, which analyzes relational features, such as co-word and bibliographic coupling patterns at different levels of authors, institutions, concepts, etc. [44]. With the purpose to explore innovation and entrepreneurial opportunities in these distinct relational structures [57], these knowledge mapping findings form the basis for roadmapping in Section 4.

3.1. Intellectual Structure

This sub-section presents both the historiographic network and the co-citation network of the overall intellectual structure, with specific intellectual contributions made by individual papers and major cited publication sources.

3.1.1. Direct Citation Network: The Historiographic Network of Main Authors

Using historiographic visualization, Figure 1 shows the existence of two main clusters in the intellectual structure of the top-cited papers, ranging from 2017 to 2022. These two main clusters correspond to research on seaports (cluster 1 in red at the top of Figure 1) and airports (cluster 2 in blue at the bottom of Figure 1). The colors were assigned by Bibliometrix, using the default color palette with the order of red, blue, green, purple, orange, and so on.

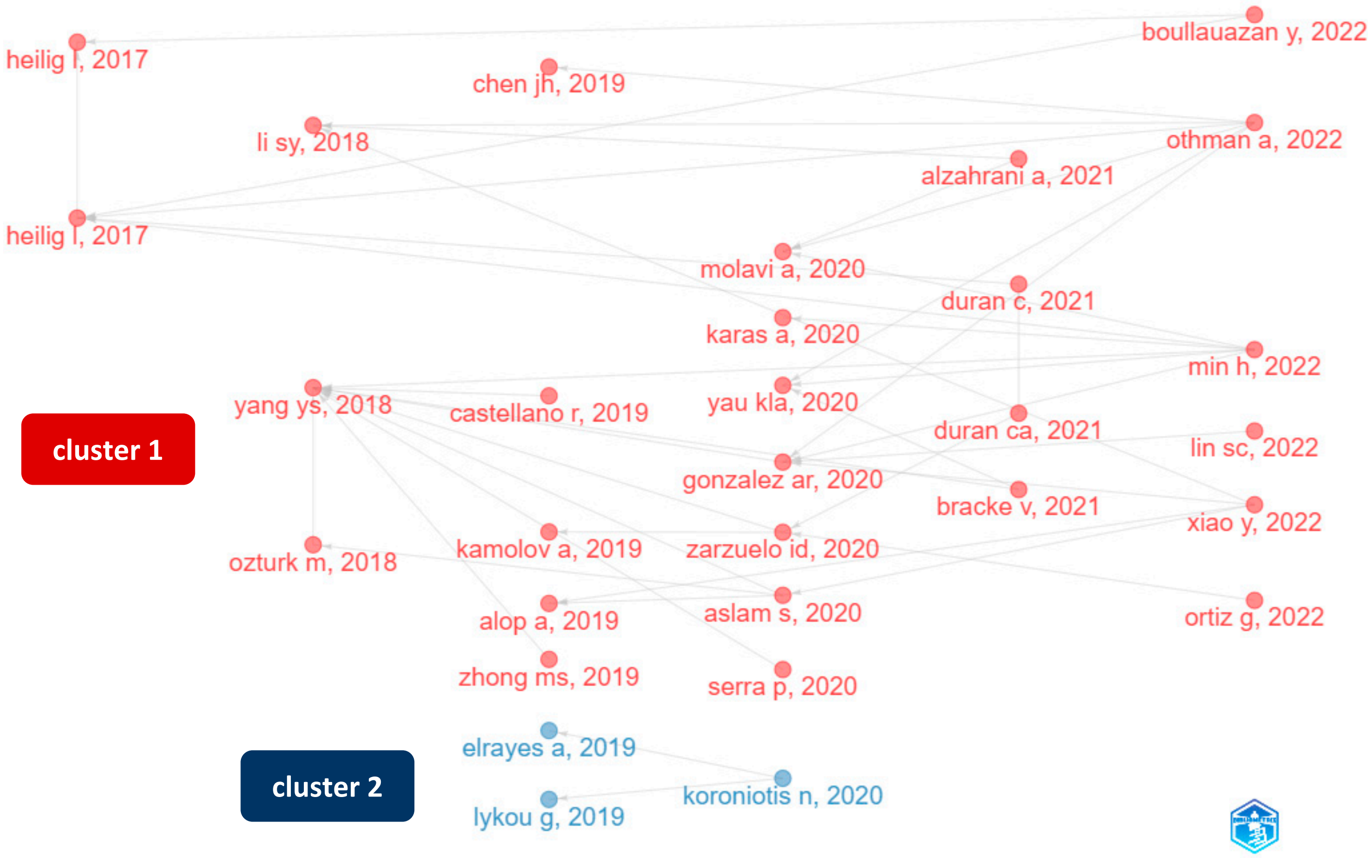

Figure 1. Historiograph: intellectual structure.

Table 2 details the information and citation metrics of some of the top-cited papers included in Figure 1 with a global citation score (GCS) value higher than 10. It should be noted that both the local citation score (LCS) and the GCS, were calculated by using Bibliometrix; they indicate the number of citations a paper has received from the local data set on intelligent ports (N = 103) and from the Web of Science database, respectively.

Table 2. Historiograph: detailed information ordered by cluster and by the GCS *.

Cluster	Paper	Title	Year	LCS	GCS
Cluster 1	Yang YS, 2018, IEEE INSTRU MEAS MAG doi:10.1109/mim.2018.8278808 [58]	Internet of things for smart ports: technologies and challenges	2018	19	131
	Heilig L, 2017, NETNOMICS doi:10.1007/s11066-017-9122-x [59]	Digital transformation in maritime ports: analysis and a game theoretic framework	2017	7	66
	Aslam S, 2020, IEEE INTERNET THINGS doi:10.1109/jiot.2020.2993411 [60]	Internet of ships: a survey on architectures, emerging applications, and challenges	2020	4	46
	Zarzuelo ID, 2020, J IND INF INTEGR doi:10.1016/j.jii.2020.100173 [34]	Industry 4.0 in the port and maritime industry: a literature review	2020	8	43
	Molavi A, 2020, APPL ENERG doi:10.1016/j.apenergy.2019.114022 [61]	Enabling smart ports through the integration of microgrids: a two-stage stochastic programming approach	2020	6	31
	Yau KLA, 2020, IEEE ACCESS doi:10.1109/access.2020.2990961 [62]	Towards smart port infrastructures: enhancing port activities using information and communications technology	2020	9	29
	Heilig L, 2017, FLEX SERV MANUF J doi:10.1007/s10696-017-9280-z [63]	Port-IO: an integrative mobile cloud platform for real-time inter-terminal truck routing optimization	2017	2	27
	Zhong MS, 2019, IEEE INSTRU MEAS MAG doi:10.1109/mim.2019.8917899 [64]	5G and IoT: towards a new era of communications and measurements	2019	2	22
	Gonzalez AR, 2020, LOGISTICS-BASEL doi:10.3390/logistics4020009 [65]	Preparation of a smart port indicator and calculation of a ranking for the Spanish port system	2020	6	17
	Ozturk M, 2018, WIREL COMMUN MOB COM doi:10.1155/2018/5379326 [66]	Energy-aware smart connectivity for IoT networks: enabling smart ports	2018	3	14
	Alop A, 2019, TRANSNAV doi:10.12716/1001.13.03.05 [67]	The main challenges and barriers to the successful smart shipping	2019	3	13
Cluster 2	Lykou G, 2019, SENSORS-BASEL doi:10.3390/s19010019 [68]	Smart airport cybersecurity: threat mitigation and cyber resilience controls	2019	2	15
	Koroniotis N, 2020, IEEE ACCESS doi:10.1109/access.2020.3036728 [69]	A holistic review of cybersecurity and reliability perspectives in smart airports	2020	3	14
	Elrayes A, 2019, INTERNET THINGS-NETH doi:10.1016/J.IOT.2018.11.001 [70]	Smart airport foreign object debris detection rover using LiDAR technology	2019	1	7

* LCS (local citation score) and GCS (global citation score) indicators were calculated using the functions for a historical direct citation network provided in the Bibliometrix package. LCS refers to the number of citations a paper has received in the local dataset on intelligent ports (N = 103), whereas GCS refers to the total number of citations a paper has received in the Web of Science database.

In relation to smart airports, the three papers in the historical direct network consist of two papers focusing on cybersecurity and reliability [68,69] and one focusing on debris detection using LiDAR technology, a remote sensing method called light detection and ranging that uses pulsed laser lights to measure ranges to the Earth [70]. Beyond these three papers shown in the historical direct network, one notable paper on smart airports, also from the perspective of Industry 4.0, integrated various standards, such as environmental impacts, docking, navigation, and object detection, into a practical decision support system using the analytical hierarchy process and fuzzy inference system, with a proposed architecture of a baggage handling system and autonomous robot units, in order to illustrate the usefulness of a smart logistics zone standard [71].

In short, the integrative smart seaport research is relatively more developed than smart airport research, the following paragraphs focus on the main body of research on smart seaports, as shown in the historical direct network.

3.1.2. Earlier Works in the Historiographic Network, from 2017 to 2018

The paper with the highest GCS (131) was published in 2018 by Yang et al. [58] It focused on the IoT as a sensing solution system for smart ports; moreover, it summarized the system requirements, detailed the architecture and operations, and discussed the required communication standards and implementation examples of structural health monitoring. Since this study detailed and described distributed sensing systems based on the common equipment that constitute the main world ports, such as automated guided vehicles and quayside cranes, it contributed to the knowledge base by surveying the IoT revolution for smart-port implementation. As such, it went beyond the conventional IoT application scenarios, including aspects, such as smart cities, smart factories, and smart homes.

The paper with the second-highest GCS (66) was published in 2017 by Heilig et al. [59] in *NETNOMICS: Economic Research and Electronic Networking*. This paper provided a conceptual framework for the digitalization and digital transformation of the maritime industry, focusing on the critical and challenging aspects of coordination and collaboration. It used game theory to perform a benefit and cost analysis at different inter-, intra-, and meta-organizational levels. To support strategic decision-making and drive digital transformation in seaports, this technology management paper inspired several other research studies [72–74] that examined the strong facilitators of digitalization to increase the efficiency and sustainability of logistics by focusing on better planning and management within and across ports. Another more technical work by Heilig et al. [63] on the building of a mobile cloud platform called "port-IO", demonstrated the real-time application of inter-terminal truck routing to solve container flow issues within a seaport with a decision support system. This paper showed that this system can reduce both costs and carbon footprint by facilitating real-time communication and context-aware logistics planning.

Other top-cited papers include a survey paper on the internet of ships [60] and an Industry 4.0 perspective [34]. The internet of ships paper by Aslam et al. [60] revealed its main paradigm, architecture, elements, and characteristics, pointing to future research areas, such as satellite communications, maritime data collection, management, analytics, and other security and privacy issues. This article was cited by other papers, such as a framework paper on smart shipping [75] and a systematic review of renewable energy sources for greener seaports, including port microgrids, and covering both technological and operational strategies [33]. Published in the *Journal of Industrial Information Integration*, the literature review paper on the Industry 4.0 perspective by Zarzuelo et al. [34] provided some suggestions to foster cooperation among key agents, such as port authorities, terminal, and port users, and port service providers for digital transformation alignment with Industry 4.0 practices. It also distinguished technologies that are more mature from those that are less ready for the port and maritime industry. It was cited by several other papers, including a two-port case study on strategic interrelationships and decision-making of Chilean port networks [74], a paper by Othman et al. [72] proposing a smart port index, and that by Boullauazan et al. [73] proposing a smart port maturity model. Another early paper is a conference paper exploring the information and intelligence potential of cloud-based IoT-enabled port terminal information for daily supervision by government authorities and private companies [76].

In synthesis, as described above in Section 3.1.2, an intellectual legacy appears to be established by both technology (especially IoT and Industry 4.0) and management (especially for strategic and real-time decision-making support systems).

3.1.3. Intermediate Work Published from 2019 to 2021

Figure 1 shows the intermediate body of works published in the period 2019–2021.

As early as in 2019, a paper on smart shipping began to raise questions on the use of IoT and Big Data for intelligent ships and smart ports [67], regarding system complexity, vulnerability, and accountability, which remain currently unresolved. Moreover, the issues of measurements and monitoring, mainly using 5G and IoT, were raised and discussed [64,77,78]. This research concern on evaluating the efficacy of ICTs for smart port application was also discussed in a paper published in *IEEE Transactions on Industrial Informatics* [79]. This paper provided evidence from interactive websites and social media marketing on port efficiency, formulating suggestions for policymakers, port authorities, and industrial sectors to identify critical areas for development and investment.

In 2020, in addition to the aforementioned paper on the internet of ships by Aslam et al. [60] and a literature review paper on Industry 4.0 by Zarzuelo et al. [34], other papers discussing the use of the ICTs or digital technologies for smart ports were published, covering the need to address greenhouse gases emission issues [62], the Spanish port system ranking [65], and the Easylog project between Italian and French regions for five ports in the upper Tyrrhenian area [80]. Furthermore, the technological innovation possibilities were further discussed for the ports of the North Sea and the Baltic Sea [81]. In relation to the use of microgrid applications and smart port system integration, a paper proposed a set of smart port index (SPI) metrics, building a model to solve both investment master and operation planning problems, while ensuring improvements in sustainability, reliability, and productivity of port operations [61].

In 2021, in addition to the aforementioned research on strategic interrelationships and decision-making [74], the discussions on the use of IoT and blockchains was updated [82,83]. A paper proposed an EU port management system based on a scalable and multi-tenant cloud-based IoT integration platform, to integrate the fragmented implementation of IoT protocols and devices, resulting in a project called Obelisk [82]. This paper pointed to the need for further development in platform scalability for microservices for IoT, as illustrated in an air quality monitoring use case deployed in the city of Antwerp. The possibilities of blockchain technologies for innovation platforms in the maritime port industry were also explored by [83], revealing the need to fill the gap between the port and its city, resulting in two scenarios and recommendations that consider both the social and cognitive aspects of Industry 4.0 in smart port applications. Finally, a major systematic review paper on the decarbonization of seaports by Alzahrani et al. [84] raised and answered several research questions. Six themes emerged for smart green seaports: (1) carbon emission reduction; (2) renewable energy adoption; (3) cost optimization; (4) smart control technology adoption; (5) regulatory landscape; and (6) best practices and guidelines. As will be further discussed in Section 4.2, these papers highlight the need to apply a socio-technical perspective [35–37], because of the various aspects of systematic innovations and changes required for green and digital transitions.

Another work by Sadri et al. [85] applied the network data envelopment analysis (DEA) to Iranian ports for their respective intelligence and greenness components. Focusing on both the level of intelligence and the level of greenness, this paper provides a multidimensional performance evaluation of 11 Iranian ports based on network DEA analysis, finding that only 5% of these ports meet the standards of intelligence and greenness. This paper also advocates for the development of green ports, especially in third-world countries, so that port authorities can review their strategies and key performance indicators accordingly. As such, it contributes to the field of green and smart port development with an analytical approach that breaks into intelligence and greenness components.

3.1.4. Latest Work Continuing the Intellectual Legacy

Several related papers were published in 2022, although with a low LCS and GCS due to the short time available to receive citations, revealing how the intellectual legacy of the past was carried in 2022. They have been published in *Maritime Policy & Management* [73,75], *Maritime Economics & Logistics* [86], *Sustainability* [72,87], and *Computer Standards & Interfaces* [88], and are discussed below.

Continuing the intellectual legacy in strategic decision-making, a paper by Boullauazan et al. [73] proposed a strategic policy tool, illustrated by a case study, for the digitalization of smart ports to optimize the "in-, intra- and outbound flow of goods and information." This definition can facilitate the capabilities of the extended port community of practice, using enabling technologies to achieve sustainable development and ensure resilient, secure, and safe operations. Adding further value to the research on quality decision-making, a paper by Xiao et al. [75] on digital empowerment for shipping proposed a smart shipping index system, based on a combination of a literature review and the Delphi method. In this system, the domain of smart ports is categorized as one of the four main domains, along with smart waterways, smart ships, and maritime intelligence. The decision-making processes can be empowered by digital systems if the stakeholders are involved in making decisions that increase efficiency, minimize costs, and reduce environmental footprints. According to the expert opinions reported in this paper, among the four domains considered, the smart ports domain is critical to achieve smart shipping. Both papers indicate the continuous push for greener, more reliable, and sustainable activities surrounding smart port development in the broader community of practice concerning the logistics information and smart shipping.

Succeeding on the legacy of the IoT [58] and Industry 4.0 [34] perspectives, the 2022 review work by Min [86] further developed a smart port architecture. By filling the gap in specifying the underlying architecture, this paper synthesized core concepts, designs, and specific monitoring milestones using content analysis. It argued that successful smart ports must improve asset utilization, reduce response time, and enhance logistics visibility. Five key factors were proposed for the successful project management of smart ports, with the additional consideration of contextualizing smart port development in global supply chains. Moreover, this paper highlighted the digital integration of end-to-end operations as key for meaningful transformation, without the need for constant intervention by human operators.

Adding to the intellectual legacy by Heilig et al. [59] on the consideration of carbon emissions and environmental impact, two papers published in *Sustainability* [72,87] continued the discussion on governance and sustainability issues of smart ports. By looking at the impact of port governance on smart port development, [87] compared Taiwan's and Spanish smart ports based on a set of evaluation criteria and key indicators. The findings show the existence of distinct differences, revealing Taiwan's focus on maritime safety in comparison to Spain's focus on operational economics, and the importance of incorporating the private sector in legislation. Similarly, the smart port index proposed by Othman et al. [72] integrated both sustainability and human resources indicators, highlighting the mutual impacts between port sustainability and human resources aspects. Both papers contributed to the intellectual development by enriching the system requirements for smart ports, especially through measurable indicators on the aspects of sustainability, governance, and human resources of smart port operations, development, and management, often at different integration levels.

Finally, the complex system perspective adopted by the earliest work on the IoT [58] inspired the implementation of digital services for smart ports, as evidenced by a paper adopting the Web of Things approach to address the need for air quality monitoring and alerting in smart ports [88]. This paper demonstrated the innovative potential of applying the more general and reusable microservice architecture to solve real-time issues with real-time data processing capabilities that support complex event processing techniques. It also highlighted the need for building smart services in a quick and agile fashion, so as to face real-time challenges with system reusability and maintenance by independent modules, thus calling for standard development on the interoperability of system interfaces.

In synthesis, an intellectual understanding has been developed and matured in relation to the integration and conceptualization of both the technology and management of smart ports at different levels and scopes, pointing to the emerging need to consider environmental, social, and governance (ESG) issues.

3.1.5. Source Co-Citation Network and Analysis: The Cited Journals as the Unit of Analysis

In order to assess the intellectual structure from the perspective of the cited journals as unit of analysis, the source co-citation network was constructed, as articulated into three clusters; it is shown in Figure 2. The first cluster in red at the bottom-right part of Figure 2, indicates the cluster of maritime, transport, and instrument research, and consists of the following journal sources: *Maritime Policy & Management*, *Transportation Research*

Part E: Logistics and Transportation Review, *Research in Transportation Business & Management*, *Maritime Economics & Logistics*, *Journal of Marine Science and Engineering*, *Transportation Research Part A: Policy and Practice*, *Journal of Transport Geography*, and *IEEE Instrumentation & Measurement Magazine*. The second cluster in green at the upper left of the figure, consists of the following journal sources: *IEEE Internet of Things*, *IEEE Access*, *IEEE Communications Surveys & Tutorials*, *Sensors*, *Future Generation Computer Systems*, *Ocean Engineering*, and *Computers and Security*. Finally, the third cluster in blue at the upper right of the figure consists of four journals: *Journal of Cleaner Production*, *Sustainability*, *Transportation Research Part D: Transport and Environment*, and *Renewable and Sustainable Energy Reviews*. Note that, throughout this paper, the reporting of the VOSviewer visualization findings follows the color scheme order of red, blue, green, and so on, which were assigned by VOSviewer by default.

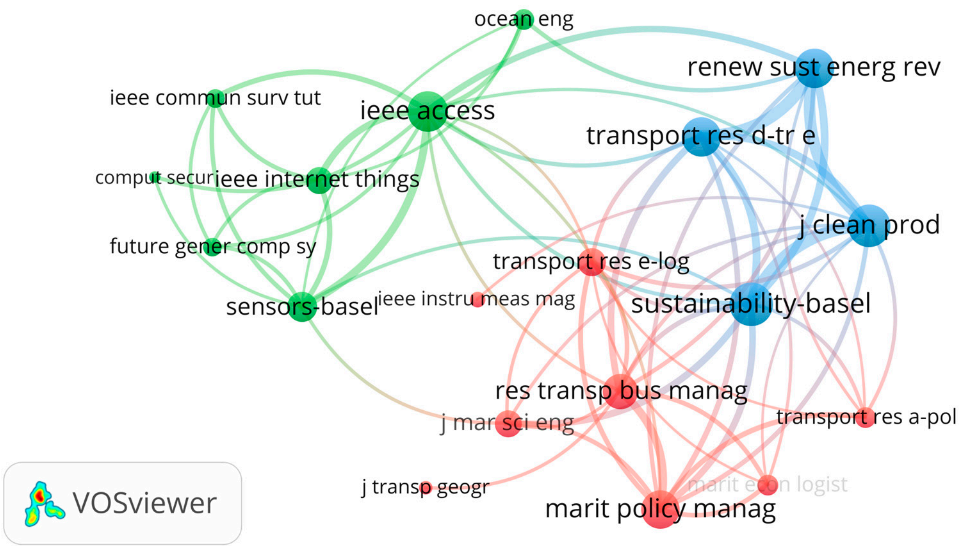

Figure 2. Source co-citation network: top-19 sources (with a minimum of 20 citations received from the local dataset).

To summarize, the intellectual structure on which the main work has been built consists of the main transportation, electrical engineering, and sustainability research journals, with policy, management, and engineering practice implications.

3.2. Social Structure: Key Publication Sources, Institutions, and Regions

To understand the collaboration patterns, a set of visualization products have been generated using VOSviewer, across key publication sources, institutions, and regions; they are shown in Figures 3–5. The social structure of the knowledge is based on bibliographic coupling analysis [89–91].

3.2.1. Key Publication Sources

The social structure of the key publication sources is illustrated in Figure 3. The main red cluster of publication sources in this figure relates to the areas of sustainability research, transportation research, maritime and coastal research, electronics engineering, and computer science; the major sources are *Maritime Policy & Management*, *Sustainability*, and *Lecture Notes in Computer Science*. The second main cluster in blue at the bottom left part of Figure 3, consists of the following journal sources: *IEEE Access*, *Information*, and *Sensors*. The isolated cluster in blue at the right part of the figure includes one publication source, i.e., *TransNav: International Journal on Marine Navigation and Safety of Sea Transportation*. The social structure of the key publication sources is multi-disciplinary, with a significant presence of technology journals.

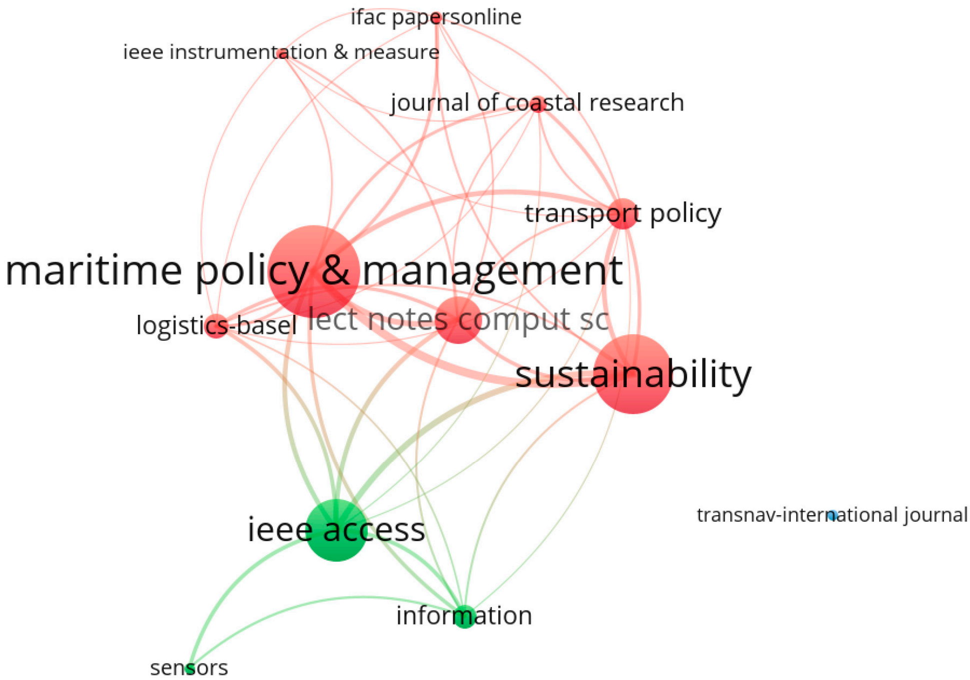

Figure 3. Bibliographic coupling network: top-12 journal sources.

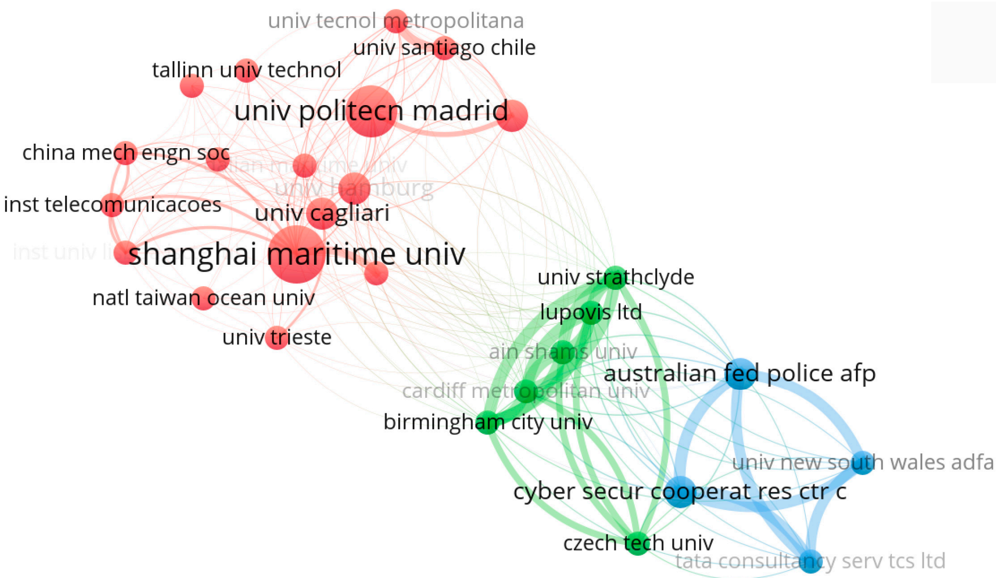

Figure 4. Bibliometric coupling network analysis: Top-27 institutions.

3.2.2. Key Universities and Institutions

Figure 4 shows the top-27 organizations that have produced at least two documents. The red cluster at top of this figure illustrates the main-contributing universities, including the Shanghai Maritime University, the Technical University of Madrid, the University of Hamburg, the University of Cagliari, the National Taiwan Ocean University, the University of Trieste, the Tallinn University of Technology, and the Dalian Maritime University. The green cluster at the center features several European and North African institutions, such as the Birmingham City University, Cardiff Metropolitan University, and Ain Shams University in Egypt. The third blue cluster at the bottom-right part of Figure 4 consists of Australian and Indian institutions primarily focusing on cyber security.

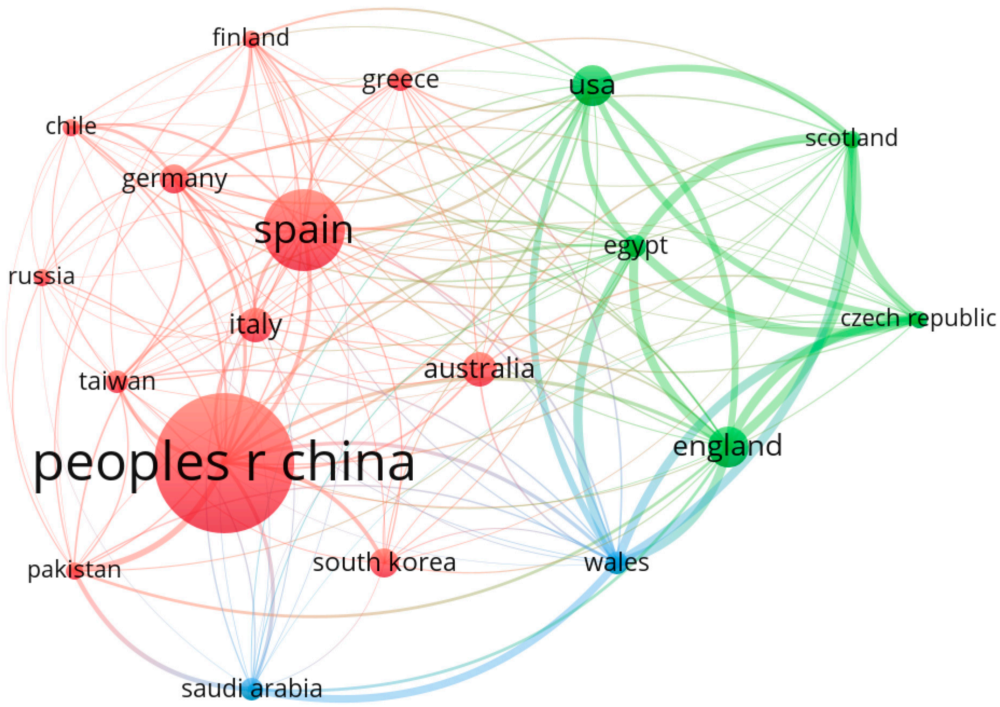

Figure 5. Bibliometric coupling network analysis: Top-19 regions/countries.

In synthesis, the overall regional representation is relatively even across major continents, with several institutions near port cities, such as Shanghai [58,64,77,92–94], Hamburg [59,63], Tallinn [67,95], Singapore [33,96], and Dalian [97–99].

3.2.3. Key Regions

Figure 5 shows the top-19 countries or regions that have produced more than three papers. The red cluster at the left part of this figure illustrates the dominant node of China, along with European countries, such as Spain, Italy, Germany, Greece, and Finland, one South American country Chile, and other Asia-Pacific countries/regions, such as South Korea, Taiwan, and Australia. The green cluster at the right part of Figure 5 includes regions, such as England, Scotland, the USA, and Egypt. Finally, the blue cluster at the bottom includes Saudi Arabia and Wales.

These findings reveal the global knowledge network of publication sources, institutions, and countries/regions, indicating the importance of institutions within and across port cities.

3.3. Conceptual Structure and Thematic Analysis

The final set of findings focuses on the conceptual structure and thematic analysis based on the authors' keywords, which aimed to reveal the overall interlinking network structure of concepts and respective research papers.

3.3.1. Conceptual Structure: Keyword Co-Occurrence Network

Figure 6 shows the keyword co-occurrence network of the top-23 keywords, generated using VoSviewer. The top keyword "smart ports" was removed as this term showed up in all papers, resulting in five clusters of concepts. The first conceptual cluster is the "Industry 4.0" cluster, in red and shown in the lower part of Figure 6; it highlights the importance of information and ICTs in building Port 4.0 and intelligent ports. The second conceptual cluster is the "sustainability" cluster in green, with associated themes, such as 5G, data, and maritime industry. The third cluster is the "smart airports" cluster, in blue and at the right part of Figure 6, with associated issues, such as security, automation, and protocols. The fourth cluster is the "digitalization-and-digital-transformation" cluster, in yellow and at the top of this Figure, with key terms, such as blockchain and seaports. The final cluster consists of IoT and smart ships, in purple and at the center of Figure 6.

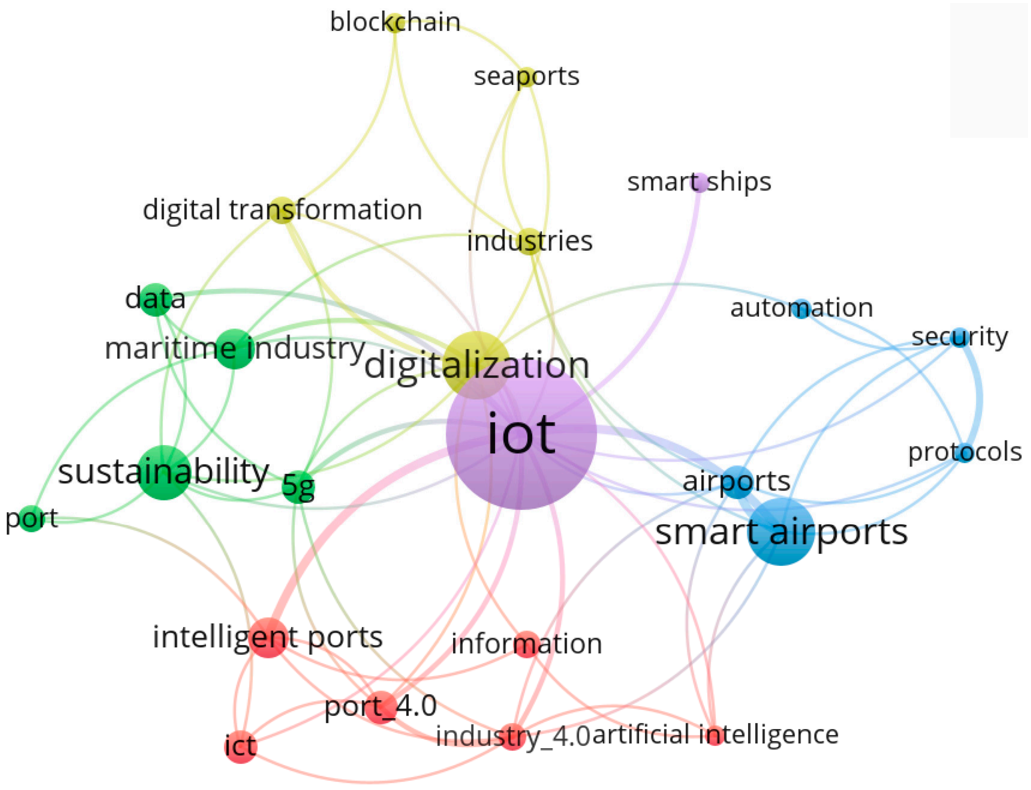

Figure 6. Keyword co-occurrence network: top-23 keywords (the top keyword "smart ports" was omitted).

Clearly, the findings of the intellectual structure analysis regarding the IoT were confirmed to have a lasting impact on the conceptual structure of the knowledge base.

3.3.2. Conceptual Structure: Theme Clusters and Topic Dendrogram

Figures 7 and 8 show the results of the in-depth analysis of the conceptual structure, using the multiple correspondence analysis (MCA) methods [100] provided by the Bibliometrix software [44]. Five clusters of keywords were identified, corresponding to the most-contributing papers, as follows: (1) industry data, IoT and ICT; (2) industry 4.0; (3) smart airports; (4) automation; and (5) protocol and security. Given the fact that the first dimension in the MCA findings accounted for 50% of the total explained variance, the overall results of this analysis could be used to cluster the top keywords. As also mentioned earlier, the cluster colors were assigned by Bibliometrix, using the default color palette with the order of red, blue, green, purple, orange, and so on. The order of the cluster colors also applies in Figure 9.

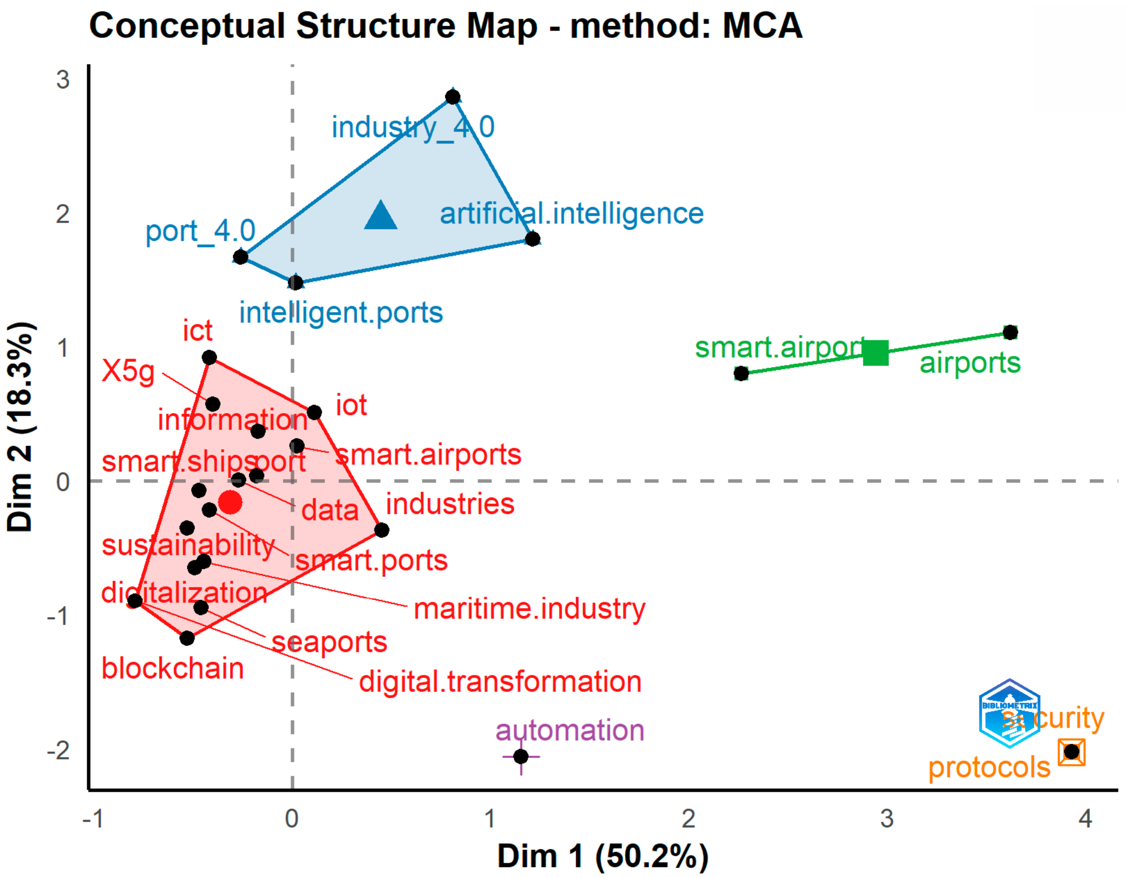

Figure 7. Conceptual structure using multiple correspondence analysis (MCA): word map of 25 terms.

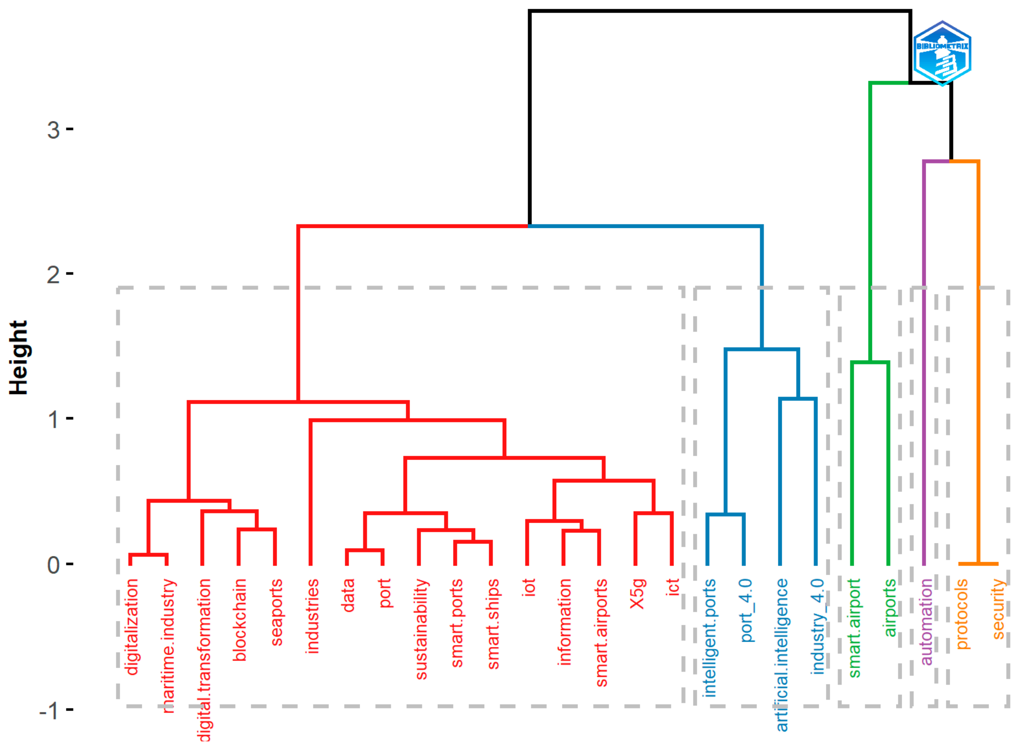

Figure 8. Conceptual structure using multiple correspondence analysis (MCA): topic dendrogram of 25 terms.

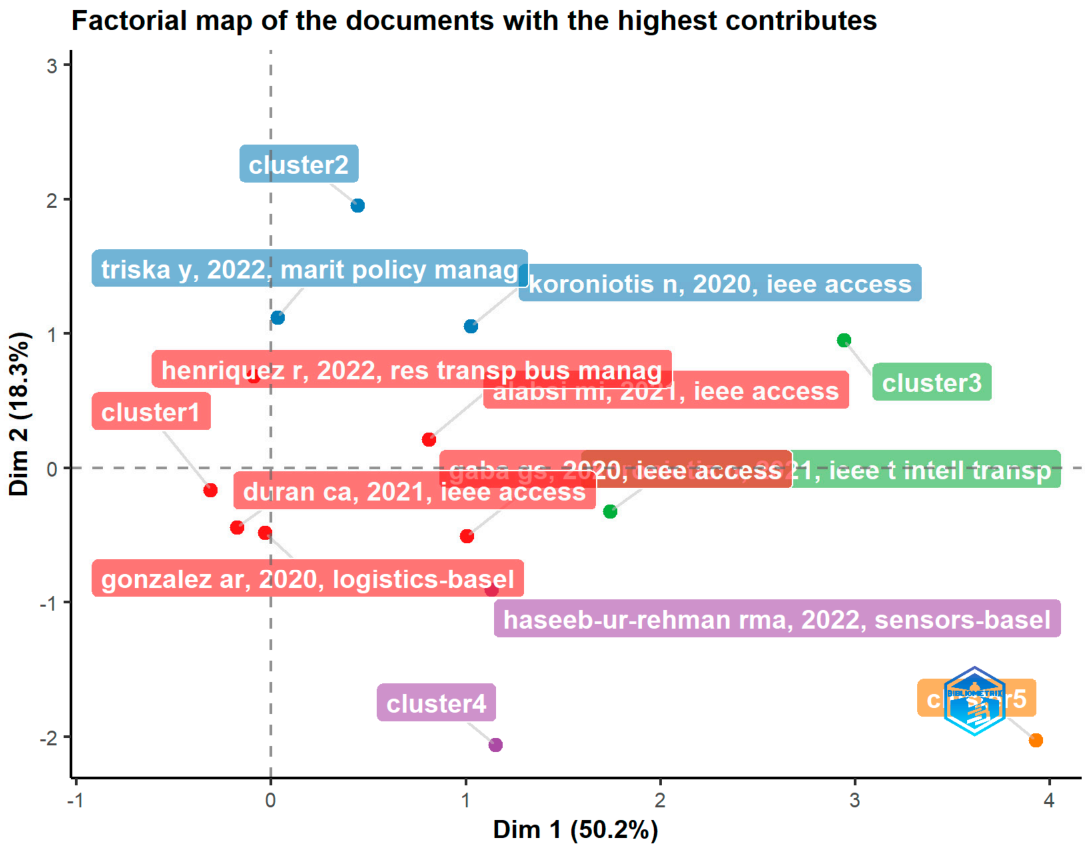

Figure 9. Top-contributing papers: using multiple correspondence analysis (MCA).

The top-contributing papers were identified accordingly, especially for the main "port innovation cluster," as shown in Figure 9. Cluster 1 features papers, such as a case study of seaports' business model innovation based on the port of Barcelona by Henriquez et al. [101], the use of crowdsourcing blockchains by Duran [83], and a smart port indicator and ranking of Spanish ports by González et al. [65]. In particular, the crowdsourcing blockchain conceptual framework, provided by Duran et al. [83], can serve as an innovation platform for the maritime port industry's need for trust, transparency, and traceability of cargo and cargo data. This research study also calls for the incorporation of public actors at the governance level in the process of decision-making. Two scenarios and recommendations are also provided in the context of Industry 4.0, considering social and cognitive aspects. Cluster 2 features a paper on smart port terminals by Triska et al. [102] and a review of smart airports cybersecurity and reliability by Koroniotis et al. [69]. Finally, cluster 3 features a case study of an industrial internet of things (IIoT)-based smart airport service by Koroniotis et al. [103].

Altogether, the bibliometric analysis based on the bibliographic data reveals different aspects of the knowledge base, providing a set of knowledge mapping of the current research fronts.

4. Discussion and Conclusions

Inspired by the findings of the bibliometric analysis, several suggestions are proposed for a roadmap to advance the integrated approach of technology management in building smart ports, or intelligent ports, as a key concern for global sustainable development. Specifically, several actions for innovation and development were formulated based on the combination of social and technical aspects of sustainable smart ports. These suggestions can be further generalized under certain conditions to shed light on the ways in which human societies can manage the risk from climate change, sea-levels rising, and supply chain disruptions.

4.1. Mapping Knowledge of Intelligent Ports

The findings of the bibliometric analysis findings allowed to answer specific questions regarding the knowledge of intelligent ports:

1. Both the intellectual and conceptual structures of the knowledge base reveal the significance of the IoT, Industry 4.0, digitalization, and supply chains, and the relative dominance of smart seaport research in contrast to the smaller, but emerging, smart airport research. The analysis of the social structure showed the existence of various clusters of key publication sources, institutions, and regions/countries.
2. Various stakeholders of intelligent ports, such as port authorities, terminal and port users, and port service providers, are seeking digital transformation alignment with Industry 4.0 practices.
3. The information and intelligence potential of cloud-based IoT-enabled port terminal information for everyday operations and management reveals several trends, opportunities, and threats regarding IoT and Industry 4.0 data governance, applications, management, and security, including short-term real-time decision-making support systems and long-term strategic ones.

Overall, the empirical findings of this study supplement the systematic review paper on the decarbonization of seaports by Alzahrani et al. [84], which identified six themes for smart green seaports: (1) carbon emission reduction; (2) renewable energy adoption; (3) cost optimization; (4) smart control technology adoption; (5) regulatory landscape; and (6) best practices and guidelines. In fact, the present study revealed the underlying technology and innovation management issues of digital transformation alignment across stakeholders in the IoT, Industry 4.0, 5G, Big Data, and AI integrated solutions.

4.2. Prototyping Ecosystem Innovation Surrounding Intelligent Ports

The alignment of stakeholders is the key roadmapping question in the present research. Digital technologies, especially in conjunction with the use of ESG and carbon emission data, can serve as the main resources of such an alignment. This section presents the results of the application of the socio-technical perspective [35–37] because of the various aspects of ecosystem innovations. Based on the empirical and theoretical literature of intelligent ports, ecosystem innovations surrounding intelligent ports can, thus, be prototyped as follows.

By framing the findings using the framework of socio-technical transitions toward sustainability as multi-actor, long-term, goal-oriented, contested, disruptive, and nonlinear processes [35–37], this study goes beyond the twin green and digital transition of ports in transforming themselves. It starts by discussing the viable business ecosystems, and concludes with an MVE [29]. Thus, advancing the positive impacts of the movement of goods and people, in general, becomes the ultimate goal of sustainable smart ports, which requires ecosystem innovations. The knowledge mapping findings provide empirical evidence to discuss which system innovations can be designed to advance the practice and knowledge of smart ports, especially their potential to achieve sustainable development goals and carbon neutrality. Seen from the viewpoint of business models for minimum viable ecosystems, sustainable and smart ports can contribute with valuable data and information that add to the twin green and digital transition of global supply chains.

This study found that the intellectual legacy of IoT and environmental impact research demands system integration at the different levels of devices, logistics information, networks, systems, or application ecosystems. The integration, thus, requires the design of overall performance indicators to include the carbon and ESG information associated with the port operations and with the goods and services they manage. Ultimately, ports manage the flow of goods and services and increase the flow of information. Among these various types of information, carbon and ESG information has yet to be integrated into a dominant innovation design of systematic changes for green smart ports. For instance, the issues of trust, transparency, and traceability of cargo and cargo data, as discussed by Duran et al. [83] in relation to its crowdsourcing blockchain innovation platform, have great potential to embed ESG and carbon information, including the carbon footprints of associated services and products. Furthermore, the work by Sadri et al. [85] evaluating ports and their respective intelligence and greenness components, demonstrates multiple analytical opportunities in understanding, analyzing, evaluating and, thus, building green and smart ports, with multidimensional and systematic considerations. Both studies promise useful and innovative design interventions regarding the carbon and ESG information provided and intermediated by ports as important gatekeeping nodes of global value chains.

To revive the intellectual legacy of decision-making in smart port planning and strategy, information-rich and -enabled, or data-driven decisions, best practices, and standards should be developed. Such a development can benefit from the socio-technical transitions incorporating ESG and carbon information into the logistics, including the mainstreaming of the carbon or GHG emissions data platform, with sustainable smart ports as the platform technology, or even as data curators and providers. The key to success is, therefore, the notion of ecosystem innovations based on reliable intelligence and analytics.

4.3. Outlining Ecosystem Innovation around Carbon and ESG Information

Based on the ecosystem innovation requirements of carbon and ESG information, a socio-technical transition framework of green smart ports is proposed, building upon the current knowledge framework delineated in this study; it is shown in Figure 10. First, the normative goals of sustainability and carbon neutrality guide the transition pathway dynamics. In fact, the present study added the considerations of social and environmental aspects to the current knowledge structure, which to date focuses mostly on the technical aspects of smart ports. Thus, both social and technical innovations are needed to transform the incumbent status of certain technologies and behaviors. Second, the techno-economic details should incorporate ESG and carbon information to provide meaningful and purposeful analytics and intelligence. For instance, system innovations are needed to build trustworthy and transparent measurements of intelligence and greenness, for both the port operations and the goods and services they handle. Finally, the explicit actor heterogeneity, as demonstrated partly by the various disciplinary, institutional, and regional mapping of the knowledge structure, is expected to be an essential resource for researchers, policy-makers, and professionals to understand, evaluate, and design system innovations at the higher level of global trade and the global supply chain.

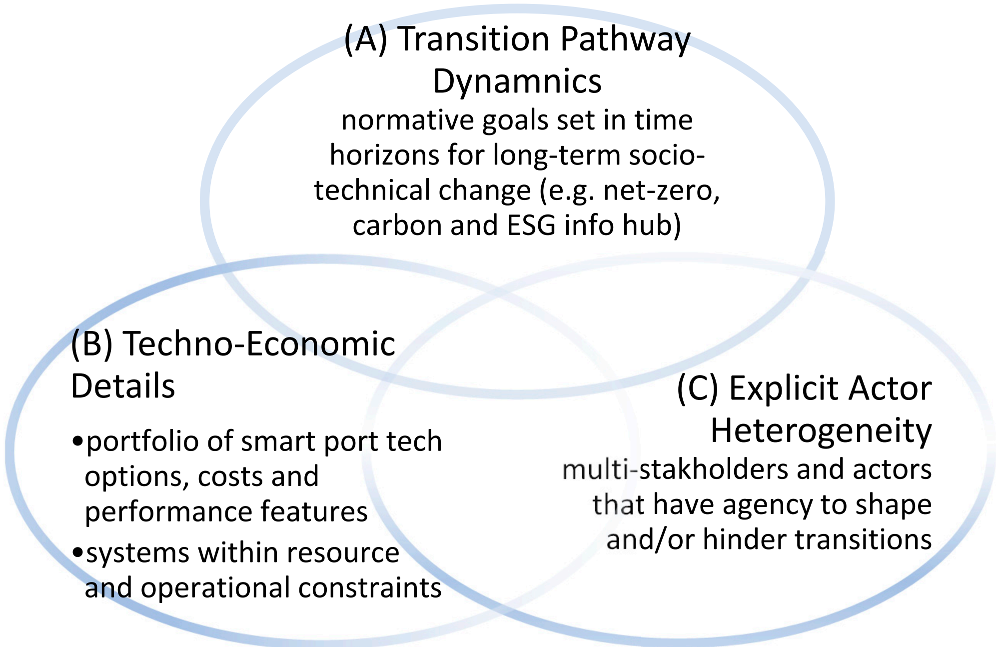

Figure 10. A socio-technical transition framework of green smart ports.

The results of the bibliometric analysis performed in the study point to the need for ecosystem innovations for the twin green and digital transition at different levels. Such a combined transition must go beyond the unit and scale at the level of ports, to include the scope and network of the interconnecting ports that constitute the backbone of the global grade and global supply chain. It is in this sense that the social structure of the current knowledge also provides a roadmap based on different disciplines, institutions, and countries for open or digital cooperation [104]. For practitioners, project managers, researchers, innovators, and policymakers alike, the initial roadmap proposed in this study includes the practical knowledge of open collaboration, open innovation, and open eco-innovation [105–107] in order to leverage technologies for good in the domains of ports and supply chains. Current research is largely dominated by seaport and maritime transportation; therefore, further research and innovation should be conducted on airports and air transportation.

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