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Ready for the Future?

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The Physical Internet and Maritime Ports: Ready for the Future?

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Abstract—*The Physical Internet (PI) is a relatively young and compelling vision about the freight transport and logistics system of the future. Besides showing how many technological and organizational innovations could converge in a real-world logistics system, it also addresses cross-industry interests such as digitalization, standardization, resilience, and environmental sustainability. In the logistics R&D community, the PI is already inspiring new designs of loading and packaging material, architectures for collaboration, and open information exchange, as well as algorithms for system-wide optimization. Our focus is on the position and role of maritime ports within the PI, as the transport hubs that facilitate most of the world's international trade. We introduce the key notions of the PI vision and expand on the unique position of maritime ports in the PI with the respective challenges this may create. Finally, we discuss the requirements for maritime ports to be ready to take up their role in the PI. We found that policy directions for ports to contribute to the development and implementation of the PI lie within the areas of transport infrastructure, (PI) standardization, advanced terminal areas, ICT hardware, information systems (IS) and platforms, and sustainability management.*

Key words: Freight transport, logistics, maritime, Physical Internet (PI), ports

I. PHYSICAL INTERNET VISION

FREIGHT transport and logistics (FTL) account for 10% of a finished product's cost on average and about 15% of the world's GDP [Mervis, 2014]. However, because of their many negative economic, environmental, and social externalities, today's transport and logistics operations are often considered to be nonsustainable. For example, transportation represents over 30% of carbon emissions, globally (IEA, 2019). The global FTL system also suffers from vulnerability and lack of resilience, as demonstrated by regular disruptions and the resulting shock effects on international trade and manufacturing.

Many technological and organizational innovations are geared to counter the negative external effects of FTL and solve its internal efficiency problems. Unfortunately, these innovations are usually viewed in isolation and hardly treated as a joint design challenge, recognizing synergies or needs for alignment. A recent integrative and overarching vision that breaks away from this isolated mode of thinking is the Physical Internet (PI). The term PI was, for the first time, introduced in June 2006 on the front page of *The Economist* [Markillie, 2006], as an analogy to the digital internet (DI).[1] Later, the PI was positioned as an all-encompassing vision for a future FTL system. The PI vision has given rise to a global movement in the logistics R&D community. Various research groups across North America, Europe, Asia, and the Middle East have started researching the PI in different contexts. ALICE, by the

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[1] See Van Luik *et al.* [2020], Dong and Franklin [2021], and Kaup *et al.* [2021] for discussions on the DI/PI analogy.

European Commission mandated logistics innovation platform, created an innovation roadmap for the PI, addressing key R&D challenges in dimensions such as technology, organization, and governance [ALICE-ETP, 2020]. As a global initiative, the annual International PI Conference (IPIC) has been held since 2014 to facilitate networking and knowledge sharing between researchers and practitioners [IPIC, 2021].

Montreuil [2020, p. 2] defines the PI as "a hyperconnected global logistics system enabling seamless open asset sharing and flow consolidation through standardized encapsulation, modularization, protocols and interfaces," where PI containers are autonomously routed through a hyperconnected network of logistics networks. The innovation is a breakthrough in the fields of material handling, logistics, transportation, and facilities design [Pan *et al*., 2017], where it seamlessly connects physical, informational, and financial flows [Treiblmaier, 2019]. By analogy with the DI, physical shipments are routed by various shared network protocols and encapsulated by multilevel modular PI containers. In the practical context of maritime ports, this encapsulation allows standardized handling of goods and data at a lower level of unitization than the current maritime container (see Figure 1).

With 80% of total global trade being transported over the sea [Hoffmann *et al*., 2018], maritime ports and operations are crucial components in the PI. However, despite its importance, the topic of maritime ports in the context of the PI has been under-addressed by researchers and practitioners. Additionally, while a vast majority of the current PI literature focuses on the scientific aspects, the practitioner's perspective has not received much attention. This article aims to discuss the relevance of the PI for managers in the port and maritime industry. It introduces the PI to those who make strategic decisions about technology, engineering, and innovation in a port and maritime environment. We aim to provide practitioners with insights into the development of the FTL system toward the PI, what this means (for them) in terms of opportunities and challenges, and the way they could contribute to its realization. We address the following key question: *How can managers in the port and maritime industry anticipate on and contribute to the implementation of the PI?*

II. Maritime Ports in the PI

Maritime ports fulfill a critical role in the FTL system. Over centuries, ports have evolved from gateways between land and sea to customer-centric (intermodal) physical and informational hubs with a focus on serving its full community of stakeholders. Ports can be regarded as dynamic organic systems [Nijdam and Van der Horst, 2017], where both economic value creation and complexity increase over time [Lee and Lam, 2016], and play an important role in both national socioeconomic, political, and globalized economic systems [Haraldson *et al*., 2021]. The United Nations Conference on Trade and Development [UNCTAD, 1999], Flynn *et al*. [2011], and Lee and Lam [2016] presented stepwise evolution frameworks for ports, describing their change from simple gateways between land and sea to customer-centric service hubs. Currently, ports are increasingly confronted with complex issues arising from recent developments, such as big data, clustering, and social and environmental concern. Future ports will need to address the increasing importance of sharing capability of real-time information among stakeholders, high-end technology driven and IT solutions, sustainability, physical and digital port connectivity, and value-added services [Ha *et al*., 2019]. Moreover, tomorrow's ports will need to go beyond the scope of connecting the local community and

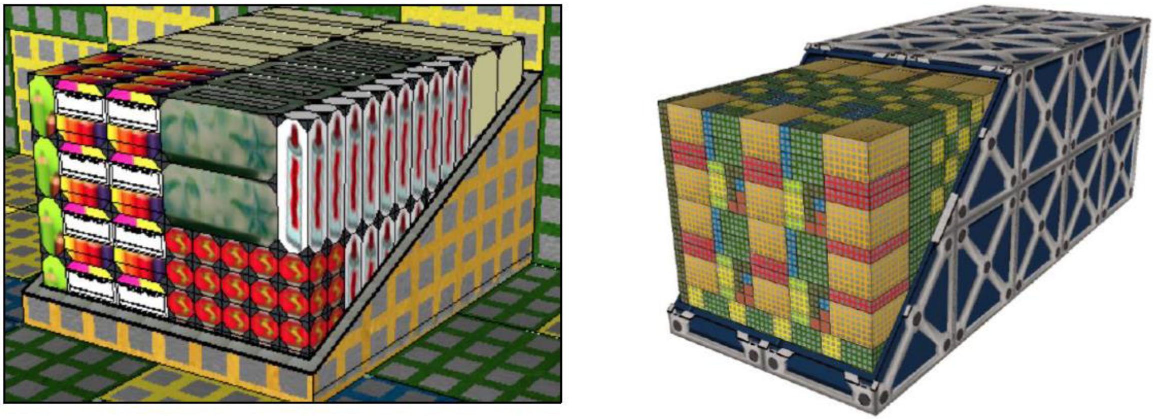


Figure 1. Encapsulation of standardized containers at different levels inside the transport container (adapted from Montreuil *et al*. [2016]).

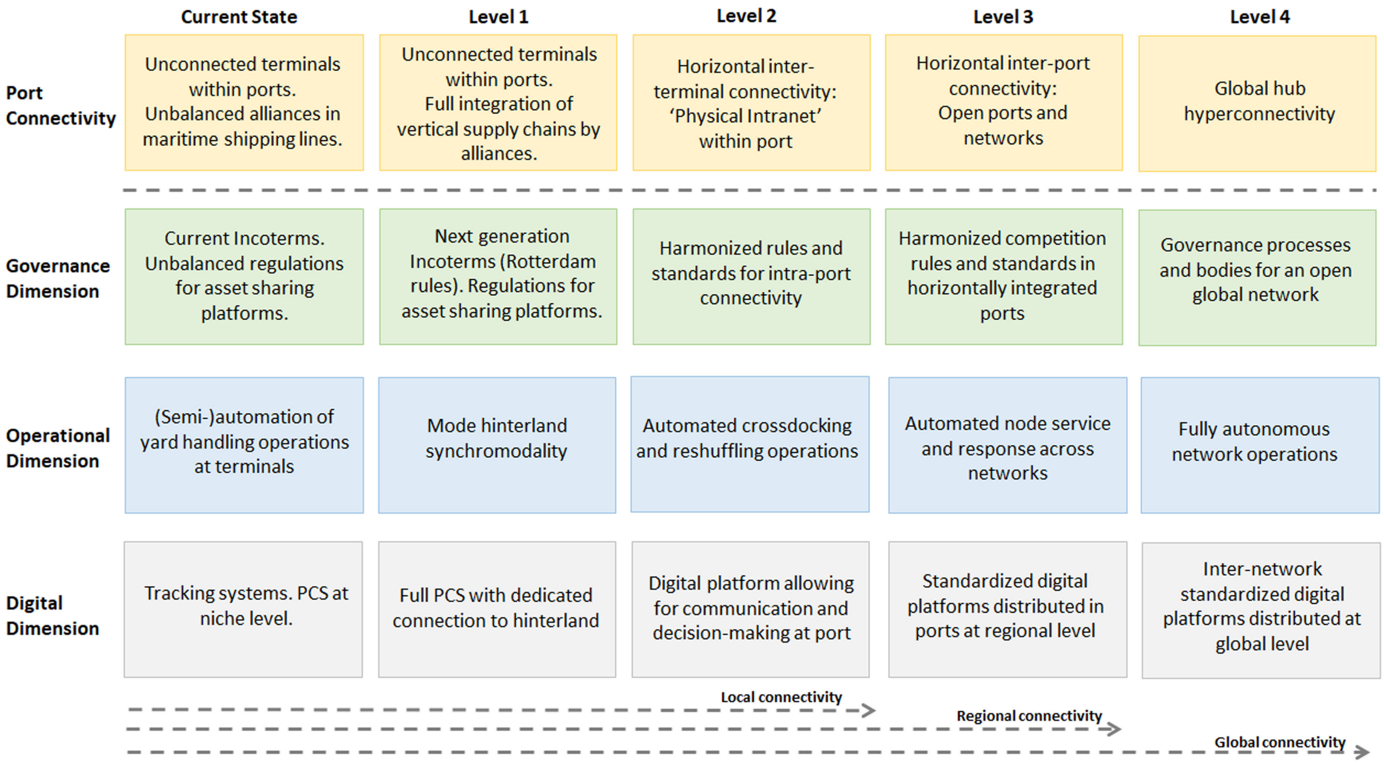
reach global connectivity in terms of both land and seaside [Port of Rotterdam, 2020]. Delenclos *et al*. [2018] argue that progressive ports are embracing the same digital breakthroughs that are disrupting other industries. These disrupters include connected information systems (IS) and platforms, cloud-based services, sensors and other Internet of Things (IoT) technologies, augmented reality, intelligent (transport) systems, blockchain, and big data.

The PI fits into the development line as the broader future context for the global FTL system, where ports are a crucial part. In line with the key development lines of the PI, Fahim *et al*. [2021a] constructed the PI Port Framework (PIPF) that visualizes the path from current ports into ports in a PI environment as follows (see Figure 2).

The *port connectivity* layer represents a combination of the (development of the) underlying PI dimensions and reflects the degree to which ports are connected internally and externally to the logistics network. The underlying dimensions represent the three main evolving elements of the PI. The *governance dimension* refers to the set of rules and protocols for a cooperative, safe, and reliable logistics network and environment. The *operational dimension* refers to the way physical operations are executed, whereas the *digital dimension* refers to the digital interconnectivity between the different stakeholders and entities in the logistics network.

Ultimately, the expectation is that the way port performance evaluation and selection will be conducted in the PI will be different than the traditional way of evaluating and selecting ports. First, the decision makers (DMs) are expected to be different in the PI. While current port users are often represented by shipping lines, logistics service providers (LSPs), and shippers [Rezaei *et al*., 2019], the PI routing protocol will require a different distribution of decisions over stakeholders, where envisioned intelligent agents, i.e., intelligent containers and vehicles, will replace current port users as DMs for port performance evaluation and selection. Second, port performance evaluation and selection are expected to be made at an operational level in a dynamic context, based on real-time information rather than at a tactical level in a static context. Fahim *et al*. [2021b] found that factors related to *port operations, costs, digital connectivity,* and *physical network connectivity* are expected to be important determinants for port performance evaluation and selection in the PI, whereas Dong and Franklin [2021] highlighted *cost, time,* and *emissions* as important logistics performance metrics in the PI.

Montreuil *et al*. [2018] claim, that for the PI to perform at the expected



	Current State	Level 1	Level 2	Level 3	Level 4
Port Connectivity	Unconnected terminals within ports. Unbalanced alliances in maritime shipping lines.	Unconnected terminals within ports. Full integration of vertical supply chains by alliances.	Horizontal inter-terminal connectivity: 'Physical Intranet' within port	Horizontal inter-port connectivity: Open ports and networks	Global hub hyperconnectivity
Governance Dimension	Current Incoterms. Unbalanced regulations for asset sharing platforms.	Next generation Incoterms (Rotterdam rules). Regulations for asset sharing platforms.	Harmonized rules and standards for intra-port connectivity	Harmonized competition rules and standards in horizontally integrated ports	Governance processes and bodies for an open global network
Operational Dimension	(Semi-)automation of yard handling operations at terminals	Mode hinterland synchromodality	Automated crossdocking and reshuffling operations	Automated node service and response across networks	Fully autonomous network operations
Digital Dimension	Tracking systems. PCS at niche level.	Full PCS with dedicated connection to hinterland	Digital platform allowing for communication and decision-making at port	Standardized digital platforms distributed in ports at regional level	Inter-network standardized digital platforms distributed at global level

Figure 2. PI Port Framework (adapted from Fahim *et al*. [2021a]).

level, by supporting the envisioned hyperconnectivity, modularity, and network structure, logistics hubs are to receive and ship modular containers encapsulating parcel consolidated by the next joint destination; exploit preconsolidation; have less direct sources and destinations; be ever more multistakeholder and multimodal service providers;

be more agile through real-time dynamic and responsive shipping times; be capable of conducting smart, real-time dynamic decisions on container consolidation and internal flow orchestration; and be active agents in the PI network, dynamically exchanging real-time information on the status of parcels, containers, vehicles, routes, and the other hubs.

In the context of maritime ports, this means that also maritime port networks need to be redesigned as globally distributed, meshed, hierarchical, multimodal networks. Additionally, ports will need to intensively collaborate with their stakeholders and other ports. This collaboration reaches beyond the borders of the port at both the land and seaside [Port of Rotterdam, 2020]. Here, the role of interconnected and interoperable IS of the different stakeholders together with information platforms, such as Port Community Systems (PCSs), will be crucial in its facilitation. Furthermore, ports need to develop digital capabilities that provide intelligence, automation, and visibility, i.e., tracking-and-tracing (T&T), not only on container level but also on individual shipment level [Fahim *et al*., 2021c]. However, to achieve the aforementioned and create a fully functioning PI, standardization of load units, interfaces, and protocols is a prerequisite [Montreuil *et al*., 2013].

Although there are various ways to decompose the PI into its main elements, in this article, we highlight and further elaborate upon the following four aspects of interest, which bear particular relevance for the port and maritime industry:

1) ports as hubs in globally distributed, meshed, hierarchical, multimodal networks;
2) open collaboration by stakeholders within, between, and outside ports;
3) digitalization leading to full visibility, automation, and intelligence;
4) standardization of load units, interfaces, and protocols.

A. Globally Distributed, Meshed, Hierarchical, Multimodal Networks

The PI is meant to be an open globally distributed FTL system, where FTL networks with their respective stakeholders and entities are connected in a network of networks [Crainic and Montreuil, 2016]. All networks should, therefore, operate under the same standards, interfaces, and protocols. The network structure of the PI is required to have the following [Meyer *et al*., 2019]:

a fast, cheap, and reliable interconnection of nodes, transport modes, and containers;

visibility on the (PI) containers (T&T);

secure and fair rewarding mechanisms for rendered services;

integration of on-demand/per-use contracts for services.

To enable efficient and sustainable transport and logistics services, Montreuil *et al*. [2018] proposed a multiplane hierarchical logistics network, interconnecting meshed networks along multiple planes. The system extends local, national, regional, and continental levels. See Figure 3 for illustrative visualization of how a shipment goes through such a network from the origin pickup and delivery (P/D) point to the destination P/D point.

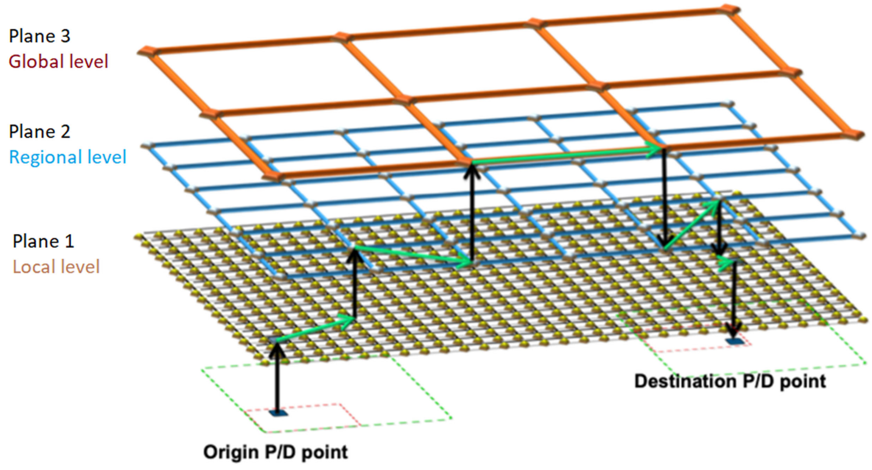


Figure 3. Hierarchy in PI networks (adapted from Montreuil *et al*. [2018]).

The multimodal meshing of networks creates many opportunities for rerouting across scales and modes. The synchronization between operations of different transport modes, also popularly named synchromodality, is considered another fundamental element of the PI [ALICE-ETP, 2021]. Decisions about switching between transport modes and routes are made in real time in response to demand variations and resource and network availabilities [Khakdaman *et al*., 2020]. In other words, in a synchromodal setting, modal choice and route decisions are not predefined and taken long in advance, instead they are taken as late as possible, based on real-time infrastructural and operational network states [Tavasszy *et al*., 2015]. The implementation of real-time and dynamic elements can facilitate optimized (re-)routing, (re-) scheduling, and modal shift, contributing to a reliable, flexible, resilient, and sustainable PI network [Ambra *et al*., 2018]. Since, in many cases, ports are multimodal transport hubs, the implementation of synchromodality will have a big impact on physical transport operations and requires digital connectivity with all stakeholders involved. As connectors between different levels of the hierarchy, ports are uniquely positioned to support the splitting and bundling of shipments.

This possibility to switch individual products across different network layers, modes, routes, and physical bundles will undoubtedly lead to more dynamic behavior of flows. Planned destinations, modes, and routes will become less important than the ability to act on the opportunity of the moment. An important implication is that port stakeholders will need to be increasingly agile and flexible to accommodate these changes. Especially, for those dealing with physical handling of individual products, such as customs authorities, one can expect a strong increase in workload. Compared to today, besides the increase in the number of small shipments due B2C e-commerce shipments, the volatile routing of these shipments implies that it will become less certain at which port the shipments arrive and when.

B. Open Collaboration Within, Between, and Outside Ports

At the core of the PI lies the concept of collaboration between stakeholders by sharing physical and digital assets. Whether the PI will be organized in a centralized or decentralized manner is still uncertain. Plasch *et al*. [2021] argued that the PI is facilitated by a central orchestrator who dynamically matches supply and demand. This neutral entity keeps track of all transport requests and resources and optimizes resource utilization and flow conditions. Dong and Franklin [2021] and Fahim *et al*. [2021b] lean toward a more decentralized operationalization of the PI, where shipments make decisions autonomously regarding their optimal paths through the network.

The main stakeholders that currently play a role in port and maritime operations are the port authority (PA), terminal operators, shipping lines, LSPs, shippers, nautical service providers, transport companies, customs, and the PCS [Nijdam and Van der Horst, 2017]. The PA is a public and/or private institution that is responsible for the management, marketing, maintenance, regulations, policies, development, and safety of the port. Terminal operators are responsible for the (un)loading of the vessels and temporary storage. Shipping lines' core business is to operate vessels and provide shipping services to its clients. LSPs provide tailor-made FTL solutions to their clients. Shippers are the initiators of the process of moving a shipment from origin to destination. Nautical service providers, such as pilotage, towage, and mooring companies, provide (un)berthing, ship maneuvering (in the port area), and mooring services to their clients. Transport companies for transport by rail, waterway, and road pick up and deliver the goods to and from the hinterland. Customs is an authority that is responsible for collecting tariffs and controlling the flow of goods into and out of a country. PCSs are neutral and open digital platforms that enable the secure exchange of data and information between public and private port stakeholders. Enhanced collaboration among these stakeholders leads to improved synchronization, coordination, and harmonization in port and maritime operations while simultaneously contributing to the visibility and efficiency of complete supply chains [Lind *et al*., 2021]. However, also here, it must be noted that the future roles of the current stakeholders in a future PI are still uncertain.

Collaboration in the maritime industry has been going on for decades and exists in many forms, ranging from slot-chartering and vessel-sharing to strategic alliances [Notteboom *et al*., 2017]. Initially, the larger shipping lines did not participate in these alliances. More recently, however, also the largest shipping lines have decided to join forces with competitors to ensure their survival and increase margins by achieving greater economies of scale and network flexibility, consequently having fewer options to differentiate, and increased difficulty to offer high service quality and visibility [Saxon, 2017]. Figure 4 illustrates how the alliances have developed over time. The forming of these alliances has also impacted ports given the larger container volumes and shift in bargaining power [Parola *et al*., 2015].

Over time, port environments have become complex ecosystems with intricate networks of stakeholders and entities. These relationships are subject to continuous change. A common denominator is increasing vertical collaboration between stakeholders. In addition to horizontal collaboration [Senarak, 2020], the maritime industry has experienced a process of vertical integration, driven by major shipping companies (e.g., Evergreen and Maersk) [Parola *et al*., 2015]. Vertical integration has benefits for multiple stakeholders in terms of, for example, terminal handling cost control, efficiency gains by achieving economies of scope, customer retention, and revenue stabilization ([Notteboom *et al*., 2017]; [Liang *et al*., 2021]). Lind *et al*. [2015] operationalized the concept of port collaborative decision-making (PortCDM), which aims at improving traffic flow and capacity management by improving the predictability of events, sharing accurate and real-time information, knowing other stakeholders' constraints and preferences, and optimizing the utilization of resources. As such, PortCDM claims to benefit all stakeholders in the (maritime) supply chain.

To facilitate the envisioned (global) hyperconnectivity between all port stakeholders and connected logistics entities, interconnected and interoperable IS are a prerequisite. IS in future ports are expected to go one step further by offering its users a single window by means of a PCS. PCSs aim at optimizing, managing, and automating port and logistics processes through a single submission of data and connecting supply chains and their stakeholders [IPCSA, 2018]. Chu *et al*. [2018] also stress that the importance of digital solutions and real-time connectivity among key logistics stakeholders, which could improve many variables throughout the entire value chain, cannot be overstated. In line with the objective of the PI becoming an open global FTL system through physical, digital, and operational hyperconnectivity [Montreuil, 2011], future PCSs aim to support T&T capabilities and interoperability across supply chains [UNESCAP, 2018].

C. Digitalization Leading to Full Visibility, Automation, and Intelligence

Digitalization has been recognized as the main enabler for ports and their stakeholders to exchange data and provide visibility to the benefit of the actors and operations throughout the logistics chains [McFarlane *et al*., 2016]. The use of (big) data and advanced analytics can help to transform ports into highly reliable and flexible automated logistics hubs [Delenclos *et al*., 2018]. Although up-front capital expenditures are high and the current operational challenges (e.g., shortage of capabilities, poor data, and siloed operations) are significant, port automation results in operational cost savings and contributes to performance enhancement and safety gains. Successfully automated ports show that operating expenses can drop between 25% and 55% and productivity can rise between 10% and 35% [Chu *et al*., 2018]. Additionally, these investments could lead the way toward a new paradigm,

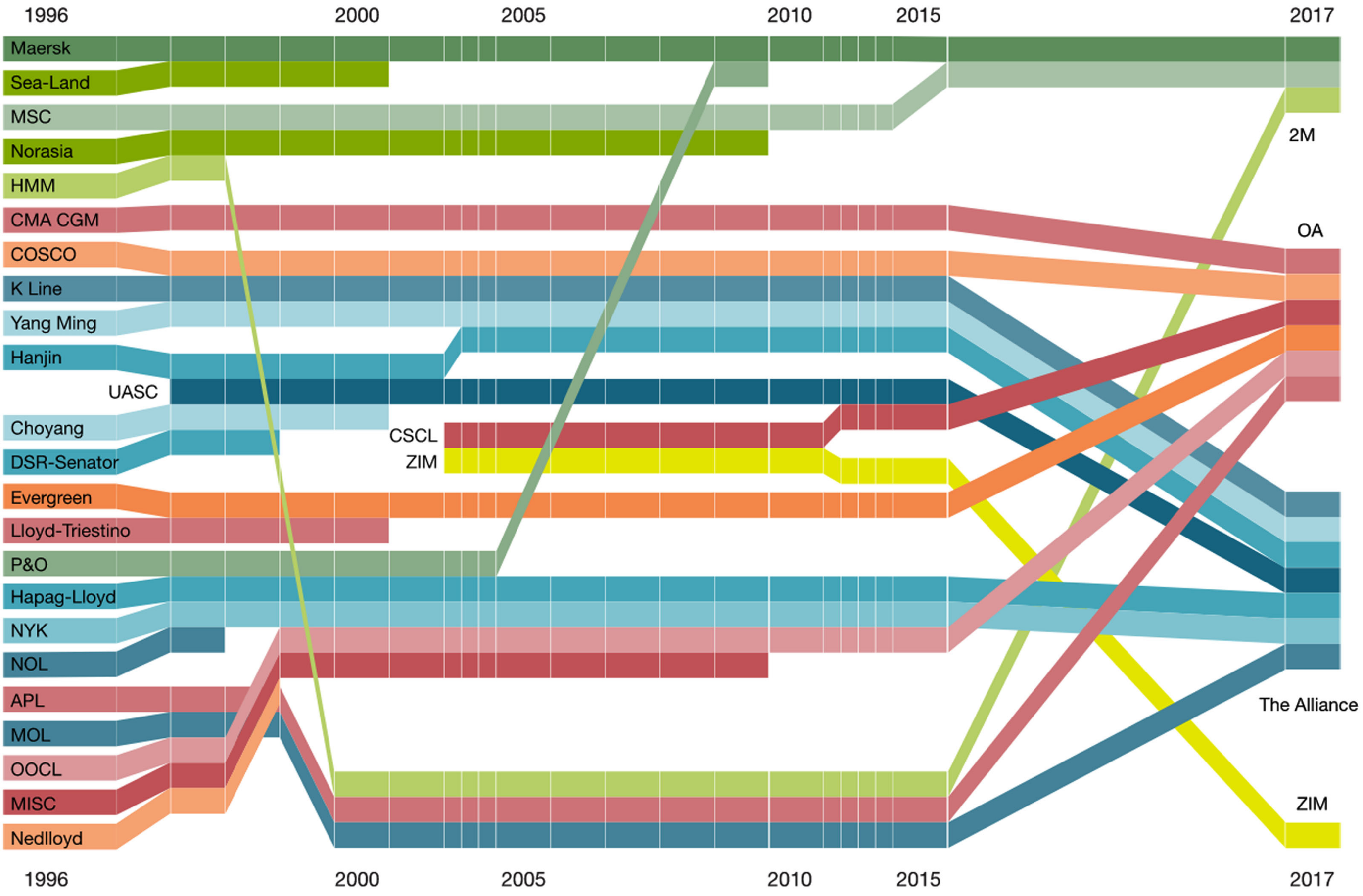


Figure 4. Development of alliances over time (adapted from Saxon [2017]).

i.e., Port 4.0, where a port's role shifts from asset operator to service orchestrator, which is in line with the PI. Port 4.0 can generate more value for port operators, suppliers, and customers alike. However, this value is not proportionally distributed across ports and their ecosystems, and hence, innovative business models and forms of collaboration will be required to realize this new paradigm [Chu *et al*., 2018].

Recent developments in the area of distributed ledger technology, such as blockchain, represent a key enabler toward the realization of PI initiatives. For example, Galvez and Dallari [2018] proposed a blockchain-based shipment tracking use case in the PI. The inherent features of blockchain include cryptosecurity, trust, transparency, programmability, and immutability of transactions in multiparty settings. In the context of port and logistics management, participating stakeholders include PAs, terminal operators, shipping lines, LSPs, and shippers. Any malicious attempts to add, delete, or modify transaction records would require a simultaneous change in all nodes, where all nodes possess the exact copy of the ledger. In the current operational settings, most logistics and port operations systems are centralized making them vulnerable to attacks and lack of trust among participating stakeholders.

Blockchain technology facilitates information and financial exchange among various stakeholders, where smart contracts are the most important feature of blockchain technology. Smart contracts enable real-time execution of transactions, based on predefined conditions and/or business rules, agreed by the stakeholders. Smart contracts are self-executing codes of business logic when agreed conditions are met. For example, when the carrier submits required documentation for approval, and its validation is automatic, based on preassigned conditions, it will minimize the time taken for goods to transit, optimize the use of resources, and save energy. Potential blockchain applications that are useful in the context of the PI include CargoX (https://cargox.io/solutions/for-transport-and-logistics/), an Ethereum-based platform that enables the safe exchange of authenticated freight documentation for multimodal logistics, Shipchain (https://docs.shipchain.io/docs/intro.html), Morpheus networks (https://morpheus.network/), and Blockshipping (https://blockshipping.net/), which enables efficient sharing of containers among carriers and others. Blockchain-based solutions can be used to provide a secure trusted environment for communication among various PI stakeholders. Ahmad *et al*. [2021] proposed various blockchain-based use cases in port logistics, such as shipment tracking, automation of port terminals, asset certification, and exchange and validation of trade documentation using blockchain technology. Blockchain-based port logistics systems can enable heterogeneous organizations to securely exchange data in real time for collaborative decision-making [Ahmad *et al*., 2021].

The adoption of decentralized and distributed technologies can contribute to a trustful, auditable, secure, and transparent digital operational environment for port stakeholders while lowering transaction costs. Applying these technologies could even make traditional freight forwarders superfluous [Port of Rotterdam, 2019]. Integrating blockchain with IoT solutions can

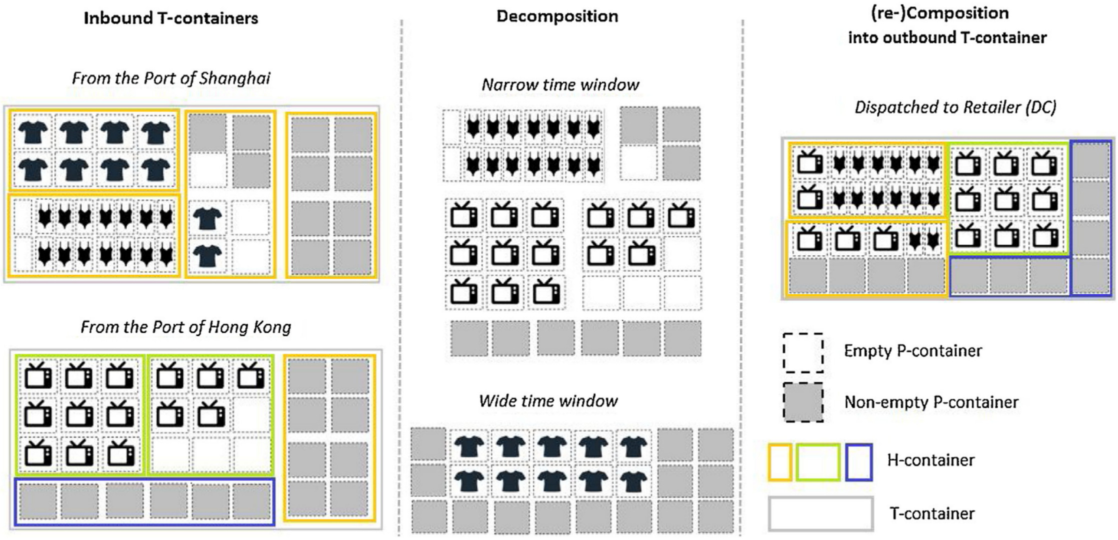


Figure 5. Illustration of the Teesport use case for the repositioning operations of PI containers at a PI port (adapted from Fahim *et al*. [2021c]).

support sensing, monitoring, T&T, and managing scarce resources to increase productivity and efficiency. The sensor nodes of an IoT network can assure real-time information sharing between all relevant port stakeholders to optimize efficiency in operations and minimize congestion [Tran-Dang *et al*., 2020]. Due to limitations on the size of file storage, blockchain-based solutions are often accompanied with off chain storage, such as InterPlanetary File System or file coin, to store the relevant information and the hash of the file that is linked and validated on the blockchain ledger. Furthermore, ports and other logistics stakeholders can leverage resource-rich cloud computing technology to store large size data, execute high-performance computations, and minimize the total cost of resource ownership. Despite the clear advantages of blockchain-based solutions, the acceptance and maturity are at the nascent stages of implementation for port and logistics operations. All stakeholders should assess the distinct advantages of automation and efficiency improvements that can be achieved via decentralization. In addition, the scalability of the transaction processing is a limiting factor to widespread adoption of blockchain-based solutions in port operations and logistics management.

D. Standardization of Load Units, Interfaces, and Protocols

Standardization is another core element of the PI. Similar to the way digital packets are encapsulated into standard data packets in the DI, the PI generalizes and further extends current standardization practices in FTL (e.g., 20 and 40 ft. sea containers). First, this is achieved by means of the *encapsulation* of all goods in PI containers before going into the PI network. PI containers exist at three levels: packaging container (P-container), handling container (H-container), and transport container (T-container). P-containers can be embedded in H-containers designed for use in handling and operations within the PI. H-containers can be embedded in T-containers, which are functionally similar to the maritime shipping containers that are currently used, exploitable across multiple modes of transportation. Figures 1 and 5 illustrate the way PI containers can be encapsulated into one another. The PI containers are designed following global standards and are easy to handle, store, transport, intelligent, connected, eco-friendly, and modular [Montreuil *et al*., 2016]. Sallez *et al*. [2016] mentioned identification, track-and-trace, state monitoring, data compatibility and interoperability, and confidentiality as key elements of the PI container. Smart PI containers have an embedded set of sensors, allowing them to communicate real-time information with their users on location, door opening and closing, vibrations, temperature, humidity, and any additional measured physical parameter of the surrounding environment [Becha *et al*., 2021]. These PI container characteristics will allow for dynamic real-time (un) loading and repositioning operations at PI ports.[2]

Second, *smart interfaces* are essential in achieving system interoperability and hyperconnectivity. From an operational port perspective, this means that processes from marine operations to crane movements to the control of yards and gates are seamlessly integrated [Chu *et al*., 2018], whereas from a digital perspective, IS and exchange platforms, such as PCSs, play a crucial role as an interface between different stakeholders and entities. Here, also standards in data (exchange) need to be emphasized, since these increase the ability to collaborate and enhance overall efficiency [Becha *et al*., 2021].

Third, the PI aims to enable hyperconnectivity through *collaborative protocols*, exploited by a wide range of stakeholders in the logistics chains. These protocols should not only ensure collaboration between logistics stakeholders and entities, but also the performance, resilience, and reliability of the overall PI network [Montreuil, 2011]. Standardized PI routing protocols are to facilitate real-time dynamic routing of intelligent agents, such as PI containers and vehicles, through the network. To connect logistics networks and services by means of protocols in the PI, Montreuil *et al*. [2012] proposed the Open Logistics Interconnection (OLI) model. The layered protocols of the OLI model provide a framework for exploiting the physical, digital, financial, human, and organizational means of the PI [Ballot *et al*., 2014].

III. IMPLICATIONS FOR PORT MANAGEMENT AND POLICYMAKERS

When considering the maritime shipping industry with its standardized containers and collaborative alliances, one might say that it is already well on its way into the PI. Still, these and many other aspects need the appropriate innovation and investment strategies. However, since the development of (the myriad of components of) the PI brings many uncertainties and ports do not possess substantive knowledge on how to anticipate on these uncertainties, sustainable long-term strategic decision-making remains challenging. Therefore, to systematically map the uncertainties in the development of the PI, and support ports in their policymaking, some contextual scenarios and policy directions for

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[2] For more details, we refer to Landschützer *et al.* [2015], which describes the methodological engineering process to develop a modular and multifunctional load unit for implementation in the PI, and Sternberg and Denizel [2021], which analyzes how the PI containers' design and characteristics determine the containers' forward and reverse flows in a network.

ports toward the PI are discussed in the following.

A. Scenarios With respect to scenarios, where Fahim *et al*. [2021a] focused on institutional developments related to the governance of the PI, Fahim *et al*. [2021d] also included technological developments, using a higher aggregate level in their analysis. Using contextual scenarios, Fahim *et al*. [2021a] also constructed some development paths for ports, using the PIPF. The development paths showed that, despite the PI's components stemming from technological innovation [Montreuil *et al*., 2013], the governance dimension, which includes collaboration, physical and digital asset sharing, new business models, legal and regulatory frameworks, and standardization, is most likely to become a bottleneck, and hence, the most critical in terms of development of the PI. In addition, the analysis showed that under the most optimistic scenario, ports as autonomous nodes in the FTL system are realized at most on a regional level by 2040, however, not globally.

B. Policy Ports will need to anticipate the above scenarios and take necessary measures to be ready for the PI, adapting to the speed at which the PI will develop in the world. Although ports are still considered to be very dissimilar from one to another [Bichou and Gray, 2004], Fahim *et al*. [2021d] developed a set of generally applicable policy directions for ports toward the PI in six key areas, as shown in Table 1.

Relating to the PIPF, from a *governance* perspective, ports could play active advisory roles to (international) governmental bodies by monitoring and evaluating the implementation of new regulations and harmonized rules, such as the upcoming Rotterdam Rules. Keeping port community stakeholders informed could allow a parallel and joint implementation among countries. Similarly, with the Consortia Block Exemption Regulation (CBER), ports could lobby in favor of its extension, or, in coordination with shipping lines, propose a more flexible version of the current CBER while still complying with Article 101 of the Treaty of the Functioning of the European Union. In addition, ports, in coordination with other port community stakeholders, and governmental and regulatory bodies, such as the International Maritime Organization, the Digital Container Shipping Association, and the International Port Community Systems Association (IPCSA) could take a leading role in the development of global standards for the (maritime) shipping industry.

From an *operational* perspective, ports should make sure that they are automated and, in a later stage, autonomous to be able to facilitate and efficiently execute the required cross-docking and repositioning operations of PI containers. Here, investments are required to update existing and develop new capabilities to achieve the desired level of interconnectivity by means of, for example, sensors and applications using IoT. Additionally, investments in port infrastructure and advanced terminal areas and facilities will be necessary. Furthermore, the development of standardized

Table 1. Policy Directions Toward the PI.

Policy direction	**Description**
Transport Infrastructure	This policy direction includes investments in the port infrastructure, such as increasing its capacity, and investments in the fore- and hinterland accessibility. These efforts could also be done in collaboration with port community stakeholders. The Maasvlakte II in Rotterdam is an example of such a project.
(PI) Standardization	Advance the administrative, nautical, legal, digital, operational, and functional standardization by taking initiative in its development in collaboration and coordination with other ports, community stakeholders, and governing bodies. Ports could, in the longer term, stimulate or enforce the use of standards by creating incentives and rules in concessions, access regulation, and pricing strategies.
Advanced Terminal Areas	Develop areas to enable automated, and in later stages autonomous, flow orchestration inside the port. The port could either develop and operate its own designated advanced terminal areas, in which repositioning operations of (PI) containers take place, or outsource to a third party. Furthermore, ports could use their concession agreements and pricing strategies to have repositioning operations taking place in the port area.
ICT Hardware	Advance the installation of sensors and wireless communication technologies in the port required by, for example, IoT services and applications. Stimulate further use and adoption of these services and applications beyond its own boundaries and among logistics stakeholders. This could be achieved by, among others, best use cases and pilot implementations, and showing the potential benefits of these applications to the port community.
Information Systems and Platforms	Advance the functional alignment and interoperability of IS. Improve the (smart) functionalities of port IS, required for, among others, the internal flow orchestration, by applying AI, IoT, and big data analytics. Develop neutral information platforms, such as PCSs, to connect its own internal port IS and to be globally digitally connected with other logistics stakeholders in both fore- and hinterland.
Sustainability Management	Develop monitoring systems, controlling safety, air and water quality, and other nuisances. Comply with environmental, working, and traffic regulations. Implement measures to reduce the negative externalities of port operations, and encourage and stimulate port community stakeholders to correspondingly implement sustainability measures by creating incentives and rules in, for example, concessions, access regulation, and pricing strategies.

operational interfaces of PI entities (e.g., PI container, PI mover, and PI conveyor) will play a crucial role. Ports, but also shipping lines, LSPs, shippers, and initiatives, such as the International Taskforce Port Call Optimization, could similarly take a leading role here and contribute to the development of these global industry standards.

From a *digital* perspective, ports could take the lead in developing industry-wide data standards and interoperable IS and platforms (e.g., PCSs) that further connect the port and its respective community to other (port) platforms, on local, regional, or global level. These PCSs should reach beyond boundaries of the port itself and extend into both the fore- and hinterland [Port of Rotterdam, 2020]. In the development of these IS and platforms, also other port community stakeholders should be included. Regional and global platforms could be developed in coordination with, and by the lead of, for example, the IPCSA. Also, when being a frontrunner in terms of digital capabilities in port communities, ports could play an advisory role toward other stakeholders.

C. Challenges One of the fundamental challenges of distributed and increasingly complex multistakeholder networks to overcome, however, is the matter of *trust and interoperability*. As value is exchanged within these networks, requirements concerning visibility, interconnectivity, and trust need to be met [Meyer *et al*., 2019]. Blockchain is a technology that might have the potential to remove or at least alleviate some of these concerns. Additionally, neutral IS and platforms, such as PCSs, could play a facilitating role here. Still, stakeholders' willingness regarding resource sharing, both digital (e.g., data) and physical (e.g., containers, vehicles, and storage), will also be key for the PI to become functional, and could become one of its main impediments [Gunes *et al*., 2021]. This could potentially be overcome by more influential and dominant ports and other port stakeholders acting as pioneers to convince other stakeholders to follow their suit, creating network effects.

Another main challenge is the development and adoption of *intelligent infrastructure*, such as sensors, wireless communication technologies, and data centers [Molavi *et al*., 2020]. Major challenges here lie in the processing power, safety and security, scale of implementation, and transparency [5GACIA, 2019]. Test beds and trials are seen as the way to go forward. This, again, could potentially be overcome by more influential and dominant ports and other port stakeholders acting as pioneers to convince other stakeholders to follow their suit, creating network effects.

An additional major challenge, which is expected to be a bottleneck in the realization of the PI, is the development and adoption of *universal standards* in data (exchange), physical entities, and their respective digital and physical interfaces. Standardization is crucial for the development of all the defined dimensions in the PIPF. For this purpose, international collaborative efforts on standardization need to be undertaken and coordinated. However, to have a fully functional open global FTL system, political alignment between major power blocks, such as the USA, China, and the European Union will be necessary, but questionable.

A similar challenge lies in the development and adoption of *business and cooperative models*, and *legal and regulatory frameworks* [Treiblmaier *et al*., 2020]. Regulatory frameworks could guide market changes, opening room for new cooperative business models and the adoption of technological innovations. However, considering the existence of disparate legal systems between and within different regions in the world, this will remain extremely challenging. Within the business and cooperative models, among others, the question of revenue sharing between the PI stakeholders needs to be addressed [Treiblmaier *et al*., 2020].

IV. CONCLUDING REMARKS

Maritime ports currently do not possess substantive knowledge on how to anticipate and contribute to the development of the PI. Through this article, we introduced the PI in a port and maritime context. At the beginning of this article, we formulated the following key question: *How can managers in the port and maritime industry anticipate on and contribute to the implementation of the PI?*

The PIPF shows that the evolution of maritime ports toward the PI can be characterized by the development of three main dimensions: the *governance, operational*, and *digital dimensions.* We also found that maritime port networks need to be redesigned as globally distributed, meshed, hierarchical, multimodal networks and that ports will need to intensively collaborate with their stakeholders and other ports. In the facilitation of this collaboration, the role of interconnected and interoperable IS together with information platforms, such as PCSs, will be crucial. Furthermore, ports need to develop digital capabilities that provide intelligence, automation, and visibility, i.e., T&T, not only on container level but also on individual shipment level. Finally, to create a fully functioning PI, standardization of load units, interfaces, and protocols is a prerequisite. As for recommendations to managers in the port and maritime industry, we proposed policy directions, through which port and maritime practitioners could contribute to the development of the PI. These policy directions lie within the areas of *transport infrastructure, (PI) standardization, advanced terminal areas, ICT hardware, IS and platforms,* and *sustainability management*.

The biggest challenges and most pressing innovation areas for the future development of the PI lie in the system's *overall trust and interoperability,* development, and adoption of *intelligent infrastructure and universal standards, business, and cooperative models*, and *legal and regulatory frameworks.* Future research and practice will need to further address these concerns as interest and applications of the PI increase.

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