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DOI
10.1016/j.futures.2021.102834

Publication date
2021

Document Version
Final published version

Published in
Futures

Citation (APA)
Fahim, P. B. M., Martinez de Ubago Alvarez de Sotomayor, M., Rezaei, J., van Binsbergen, A., Nijdam, M., & Tavasszy, L. (2021). On the evolution of maritime ports towards the Physical Internet. *Futures*, *134*, Article 102834. https://doi.org/10.1016/j.futures.2021.102834

Futures 134 (2021) 102834

Contents lists available at ScienceDirect

Futures

journal homepage: www.elsevier.com/locate/futures

On the evolution of maritime ports towards the Physical Internet

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A R T I C L E I N F O

Keywords:
Physical Internet
Logistics
Freight transport
Maritime ports
Scenario development
Delphi study

A B S T R A C T

The Physical Internet (PI) is a novel, comprehensive and long-term vision of the future global freight transport and logistics (FTL) system, which is aimed at radically improving its efficiency and sustainability. As research on the PI concept is still young, the functioning of maritime ports in the context of the PI is still underexplored. Our aim is to contribute to the scientific debate about radically different futures for maritime ports around the world, by identifying their possible future development paths towards the PI. We construct an evolutionary port development framework that identifies the main dimensions of the PI in relation to ports, including governance, operational, and digital aspects. To design the future development paths towards the PI, we conducted a scenario analysis and used a Delphi survey amongst port development and PI experts. The resulting expectation is that a fully globally functioning of the PI may not be reached by 2040. Also, our analysis shows that global governance of FTL systems is critical for the pace of development and adoption. Building on the identified potential future development paths, we provide a discussion, relevant for port authorities and other stakeholders, as well as avenues for future research.

1. Introduction

Over centuries, maritime ports have evolved to function as critical facilitators of global trade, affecting not only the local economy, but also the way that national and regional economies operate (Brooks et al., 2014). They can be seen as highly complex systems due to the large and diverse number of stakeholders involved and the types of services they offer; not only functioning as nodes of the logistics network, but also as a location of industrial and value-added services (Nijdam & Van der Horst, 2017). With ports being highly asset and capital intensive (Rodrigue, 2010), coping with future uncertainties is crucial so that port authorities (PAs) can determine appropriate strategies and allocate proper investments. Failing to respond to market changes and developments in freight transport and logistics (FTL) systems in a timely manner can result in negative consequences, not just for the port itself, but also for the local, national and regional economy (Halim et al., 2016). In order to deal with uncertainties, a common practice is to develop scenarios (Melander, 2018).

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https://doi.org/10.1016/j.futures.2021.102834
Received 20 October 2020; Received in revised form 27 August 2021; Accepted 1 September 2021
Available online 10 September 2021

At the basis of this research lies a young conceptual design of the global FTL system that radically reshapes the way physical objects are currently moved, stored, realized, supplied and used: the Physical Internet (PI) (Montreuil et al., 2010). Montreuil et al. (2013: p. 1) defined the PI as an “open global logistics system founded on physical, digital and operational interconnectivity through encapsulation, interfaces and protocols”. Because of its complexity, and the change in paradigm it implies (Montreuil et al., 2010), an idea of this magnitude is expected to have a profound impact on all actors involved in the FTL system in the future. Hence, albeit recognized as a promising vision with a growing number of (scientific) publications (Pan et al., 2017), the development of the PI requires collaborative research initiatives by academia, industry, and governmental institutions. On a European level, for this purpose, the European Commission (EC) established ALICE, a European Technology Platform (ETP) (ALICE-ETP, 2021). On a global level, annually, the International PI Conference (IPIC) is being held to progressively share and develop knowledge on the topic of the PI (IPIC, 2021).

With 80 % of the total global trade being over sea (Hoffmann et al., 2018), the maritime transport system can be expected to be significantly affected by the developments towards the PI. However, despite its potential significant implications, the study of maritime ports in the context of the PI remains vastly underexplored. As a result, ports currently lack substantive knowledge on the manner in which the global FTL system will develop towards the PI, and the way they could anticipate on these developments.

The primary objective of this paper is to generate plausible development paths for the evolution of maritime ports towards the PI. When facing much uncertainty, as in this case with the development of the PI, expert opinions are suggested as a most reliable source for future predictions (Durance & Godet, 2010). A common technique in transport scenario studies is the Delphi method (Melander, 2018). It allows for a systematic solicitation of anonymous informed judgements on a particular topic through a (multi-stage) process, where feedback of a group’s opinion is provided (after each round) (Gnatzy et al., 2011; Turoff, 1970; Von der Gracht & Darkow, 2010). A secondary objective of this paper is to derive implications for strategic decision-making of PAs. As ports and their infrastructures are asset heavy with high investment costs and needs (Notteboom, 2016; Parola et al., 2013), a thorough understanding of the manner in which the FTL system develops is crucial for sustainable long-term strategic decision-making (Taneja et al., 2010). By analysing the constructed port development paths under the different scenarios towards the PI, PAs can gain insights into which policies might be useful in which particular scenario and point in time.

The contribution of this paper is twofold. Firstly, we construct an evolutionary port development framework that shows the evolution of a today’s maritime port into a *PI Port*. This framework identifies the main dimensions of the PI in relation to ports: the governance-, operational-, and digital dimension. Additionally, the framework shows how the dimensions evolve over time and result into local, regional, and global connectivity of ports. Secondly, we design potential development paths of maritime ports over time under the development of the PI. The main challenge here is to empirically predict the relationship between external factors and port development towards the PI.

The remainder of the paper is organized as follows. Section 2 provides a review of the relevant bodies of literature for our research. In Section 3, the methodological approach is outlined. In Section 4, the construction of the PI Port Framework (PI PF) and the contextual scenarios are presented and discussed. Section 5 presents the results from the Delphi study and the derived PI Port Development Paths (PI PDPs). Section 6 presents a discussion that includes the validation, and some managerial implications and recommendations for PAs. Section 7 ends the paper by means of a conclusion and recommendations for future research.

2. Literature review

We first explore the literature around the subject of port development in the context of the PI. We look at three bodies of literature to explore the subject from three different angles: (1) the PI; (2) port development; and (3) scenario development.

First mentioned in the domain of logistics in June of 2006 on the front page of The Economist (Markillie, 2006), the term PI and its potential economic, environmental, and societal contributions were more extensively elaborated upon by Montreuil (2011). Through resource sharing, both physical and digital, among stakeholders, and the design of standardized interfaces and protocols for seamless interoperability, the transport of goods in the PI are optimized with regard to costs, speed, efficiency, and sustainability (Sarraj et al., 2014). By analogy with the digital internet (DI), physical shipments are encapsulated into modular containers on multiple levels and sent through a hyperconnected network of logistics networks to their final destinations (Ballot et al., 2014).

The introduction of the PI sparked the interest of academia, industry, and governmental institutions. Following the identification of the main technological innovation (Montreuil et al., 2013), researchers investigated the vision at different levels of abstraction by means of using a wide range of methodologies. A simulation study, based on the supply flows of the top 100 suppliers of two of the main food retailers in France, showed inspiring results on the potential of the PI. Cost savings ranged from 4 % to 26 %, along with a potential threefold reduction in greenhouse gas emissions (Ballot, Gobet, & Montreuil, 2012). Conceptual designs of road and railway hubs in the PI were addressed by Ballot, Montreuil et al. (2012) and Meller et al. (2012), while Crainic and Montreuil (2016) proposed a framework linking concepts of City Logistics to the PI. The layered Open Systems Interconnection (OSI) model, which explains the DI standards and protocols, was analyzed and translated into the PI’s equivalent, the Open Logistics Interconnection (OLI) model (Colin et al., 2016; Montreuil, Ballot et al., 2012). The analogy between the DI and the PI was further investigated by Sarraj et al. (2014) and Van Luik et al. (2020). Dong and Franklin (2021) proposed a conceptual framework for the PI network using the DI as a starting point, extending into a way that logistics metrics could be dynamically optimized. Business models as well as new regulatory frameworks have been identified as important challenges to address in this new logistics paradigm (Montreuil, Rougès et al., 2012). Other works studied the topics of standardized container selection (Lin et al., 2014), and dispatching models by means of mathematical models (Venkatadri et al., 2016). Additional optimization and simulation studies were conducted on different types and levels of transport and logistics operations (e.g. Faugère & Montreuil, 2020; Krommenacker et al., 2016; Montreuil et al., 2018; Pan et al., 2015). Landschützer et al. (2015) and Sternberg and Denizel (2021) studied the modularity aspect of the PI in more detail. Regarding maritime ports, more recently, Fahim, An et al. (2021) proposed an information architecture that enables track-and-trace capability in PI ports, whereas Fahim, Rezaei et al. (2021) investigated intelligent agents' port performance evaluation and selection preferences in the context of the PI. Lastly, various literature reviews appeared that provide a perspective on the increasing body of knowledge around the concept of the PI, and define future research agendas (e.g. Ambra et al., 2018; Treiblmaier et al., 2020). Although over the past decade the number of publications, and covered research areas and methods within the PI are growing, the important topic of maritime ports has been heavily underrepresented in the PI literature. In addition, a wide range of research methods has been applied to contribute to the development of the PI, however, a systematic scenario study that maps the uncertainties in the development of the PI is still lacking.

A second relevant stream of literature concerns maritime port development. Giving a unified definition of ports is a challenging task due to their multifaceted nature. Institutional, administrative or even organizational disparities hinder a comprehensive approach to maritime ports in general (Bichou & Gray, 2005). In 1992, the United Nations Conference on Trade and Development (UNCTAD) proposed an initial generational framework that categorized ports into *port generations* that shows how these, over time, have adapted from traditional gateways between land and see with (un)loading activities (first generation ports (1GP)) into ports that offer a wider range of logistics and value-added services (3GP) (UNCTAD, 1999), as a result of global containerization and globalization (Beresford et al., 2004; Pettit & Beresford, 2009). The 4GP, which could be physically separated but linked through common operators or common administration, was added in 1999 (UNCTAD, 1999). However, different interpretations have been given to what the 4GP precisely entails (Paixao & Marlow, 2003; Verhoeven, 2010). In 2011, Flynn et al. (2011) proposed ports in a 5GP model as customer-centric and community focused, which aimed to satisfy port users' multi-faceted (business) needs, while simultaneously meeting the community stakeholder requirements. Building upon this 5GP model, Lee and Lam (2015) presented a modified version of the 5GP to evaluate inter-port competition between major ports in Asia. In line with the presented port generations, Lee and Lam (2016) argued that ports need to continuously adapt to their external environment by changing economic and trading patterns, new technologies, legislation, and port governance systems. To demonstrate the evolution of ports, they developed a framework, in which port generations evolve along a *port ladder* that describes how ports are continuously adapting to an ever changing environment. A slightly different way of considering port development is from a spatial perspective. A well-known framework from this perspective is the *Anyport* model, proposed by Bird (1971). However, since we aim to consider port development over time into the PI, the remainder of the paper will continue to focus on the generational port development models. Although, over the past decades, various (generational) port frameworks have been proposed, none of them has incorporated the PI.

The scenario development literature that deals with uncertainties inherent in futures studies is a relevant third stream of literature. Scenario development has notably evolved since its military origins at the end of World War II, where several typologies have been proposed to enhance the field of futures studies (e.g. Kahn & Wiener, 1967; Marien, 2002; Van Notten et al., 2003). Börjeson et al. (2006) distinguished between three main scenario categories on the basis of questions: predictive scenarios – what will happen? –, explorative scenarios – what can happen? –, and normative scenarios – how can a specific target be achieved? While normative scenarios aim to reach a particular state in the future, predictive and explorative scenarios simply outline possible futures without any indication of desirability (Van Notten, 2006). Contextual scenarios are also considered as explorative scenarios. These provide insights into possible future states of a system, while focusing on the external environment, or context, of that system, which cannot be influenced by the decision-maker (Enserink et al., 2010). To construct scenarios, both qualitative and/or quantitative input can be used (Van Notten, 2006). Qualitative input is considered suitable for higher levels of uncertainty, where relevant information cannot be quantified. In these cases, participatory approaches are used (e.g. Börjeson et al., 2006; Enserink et al., 2010). Quantitative input is considered suitable whenever information can be accurately quantified, so that (computer) models such as scenario discovery can be used (Halim et al., 2016).

For decades, many scenario studies have been applied in practice. The global oil and gas conglomerate Shell, for instance, has extensively been working on oil consumption and production forecasts since the 1970s, which allowed it to better adapt to sudden fluctuations (Schoemaker, 1995). Halim et al. (2016) used a model-based approach to scenario discovery, which has been used to assess potential vulnerabilities for the Port of Rotterdam, while Cooper (1994) investigated the logistics futures in Europe by means of Delphi-based scenarios with over 200 consulted experts from 6 different countries. The Delphi method endeavors to systematically obtain experts' opinion consensus about future developments and events. It is an expert opinion-based forecasting method in the form of an anonymous (multi-round) survey process, where feedback of group opinion is yielded (after every round) (Delbecq et al., 1975; Linstone & Turoff, 1975; Rowe & Wright, 2001). Using a similar methodology, three scenarios were generated to assess the carbon footprint of freight transport in the UK for 2020 (Piecyk & McKinnon, 2010). Von der Gracht and Darkow (2010) conducted another extensive Delphi-based scenario study on the future of the logistics services industry in the year 2025. Many other examples of participatory approaches, with Delphi as a common method, can be found in transport futures literature (e.g. Liimatainen et al., 2014; Schuckmann et al., 2012; Tuominen et al., 2014). Although many scenario studies have been conducted in the field of FTL, none incorporates the PI.

From the review of the three most relevant streams of literature, the following gaps can be derived. Firstly, there is nearly no literature available that explores (the future role of) maritime ports in the PI. Secondly, an evolutionary port development framework, which includes multiple dimensions (governance, operational, and digital) and describes the evolution of ports over time into the PI, has not yet been presented. Thirdly, various scenario studies in the domain of FTL have been conducted, to the authors' knowledge, however, there is no study yet available that systematically uses scenario development to describe the evolution of the PI. Fourthly, the Delphi method has not yet been applied to any study related to the PI in general, and to generate potential development paths of maritime ports towards the PI, more specifically. The latter two gaps can be considered methodological, while the first two can be considered as literature gaps.

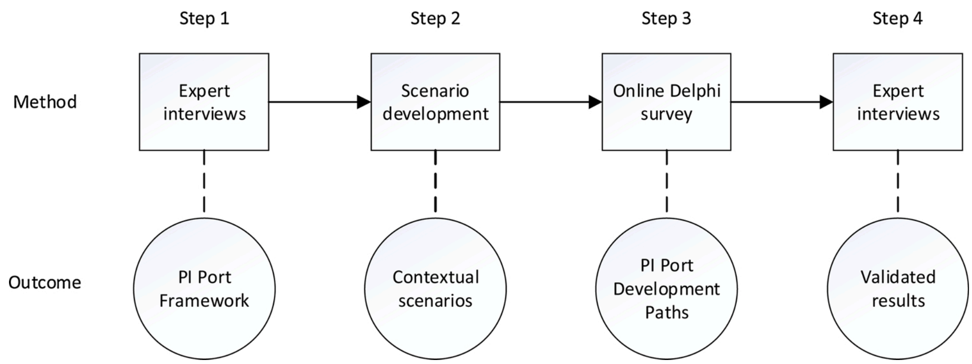

Fig. 1. Research process.

Considering the significant impact that the development towards the PI could have on ports and the fact that ports are highly asset and capital intensive (Rodrigue, 2010), gaining understanding about the (future) uncertainties that the PI could bring is crucial to decision-makers. Hence, by constructing an evolutionary port development framework, applying scenario development, and developing potential pathways for ports towards the PI, we provide PAs and other relevant stakeholders with insights and recommendations to support them in their strategic decision-making.

3. Methodology

This section introduces the methodology that is used in this research. As indicated in Fig. 1, the research process starts with expert interviews for the construction of the *PI Port Framework (PI PF)* in Step 1. These expert interviews are necessary input for the development of the conceptual PI PF. Next, in Step 2, a *scenario development* is conducted to obtain the different *contextual scenarios* towards the PI. Both the PI PF and the contextual scenarios serve as input for the *online Delphi survey* in Step 3. Here, by means of combining the PI PF and the contextual scenarios with the expert panelists' opinions, the *PI Port Development Paths (PI PDPs)* are derived. Lastly, in Step 4, to validate our obtained research outcomes from the online Delphi survey, we, again, conduct a series of expert interviews. The methods and outcomes will be explained in further detail below.

3.1. Expert interviews

Regarding the construction of the PI PF, a total of four interviews are conducted with experts, located in Germany, The Netherlands, and the USA. These experts include a Supply Chain and Logistics professor from the Georgia Institute of Technology, a professor in Freight Transport and Logistics from the Delft University of Technology, a professor in Operations Management and Operations Research from the University of Groningen, and a Strategy Researcher from Fraunhofer – IML. These experts spoke on behalf of larger communities of PI experts, both in Europe and the USA. We identify and evaluate these experts through their scientific publications and overall contributions to (the development of) the PI. The expert interviews follow an unstructured format to allow experts to freely express their opinions with a minimum bias from the interviewers. See the respective interview setup in Appendix A.

Additionally, to discuss and validate the obtained results, we conduct a series of semi-structured interviews with thirteen leading experts from both research institutions and industry. By including both academic and industry experts, we aim to obtain more balanced observations and results from both a practical and theoretical perspective. Also, the field of PI is still at a research stage and not yet fully implemented in practice. This means that, other than taking into account the opinion of real-world decision-makers, we need to know about the opinion of researchers, which is another reason why we have collected data from both groups. In these validation interviews, we present our results in terms of the obtained statistics from the Delphi survey and derived PI PDPs to the experts. The seven experts from research institutions included professors that are specialized in FTL, ports, and the PI from the Delft University of Technology, Georgia Institute of Technology, Kedge Business School, Kuehne Logistics University, Mines Paris Tech, University of Antwerp, and University of Groningen. The six experts from industry include Innovation and Strategy Managers from Groningen Seaports, Port of Algeciras, Port of Antwerp, Port of Barcelona, and Port of Rotterdam. Please find the respective validation interview setup in Appendix B.

3.2. Scenario development

Taking the levels of uncertainty around the development of the PI into consideration, *contextual scenarios* of a qualitative nature are considered most suitable. For the purpose of the development of these contextual scenarios, a *scenario logic* approach is used (Enserink et al., 2010). Here, the first step is to identify the *contextual factors*, which can be defined as variables that influence the development, performance, and outcome of a system, however, cannot be influenced by the problem owner herself. In our research, these factors are identified through a review of academic literature (e.g. Hahn, 2020; Notteboom, 2016; Tavasszy, 2018) and industry reports (e.g. DHL, 2012; Nowak et al., 2016; Nextnet, 2017; Port of Rotterdam, 2019a, 2019b; Snabe & Weinelt, 2016; WEF-BCG, 2014), in combination with expert interviews. Next, the identified contextual factors are clustered into a set of *driving forces*. In establishing the driving forces, it should be taken into account that these are, at least to a large extent, independent from of other driving forces. Based on their levels of *uncertainty* and *impact*, the most relevant driving forces are selected, after which the scenario logic can be constructed. Since including all uncertainties within the global logistics system could lead to generating a great number of scenarios (Halim et al., 2016), for reasons of practicability and the ability to provide meaningful results, we initially aim for a set of between three and eight scenarios, which is in line with other transport scenario studies (e.g. Bradfield et al., 2005; Melander, 2018; Tuominen et al., 2014).

3.3. Online Delphi survey

As Fig. 1 indicates, after the contextual scenarios development and the construction of the PI PF, an *online Delphi survey* is conducted. Since its introduction by the RAND corporation around the late 1950s (Dalkey & Helmer, 1963), the use and number of different types of Delphi studies has grown, where applications range from the traditional method to a roundless Real Time Delphi (Melander, 2018). In this paper, the employed Delphi study is based on the classic procedure, which is among the most approved variants (Von der Gracht & Darkow, 2010). However, since various researchers revealed that much of the opinions of a study change over time, and therefore, more reliable study outcomes occur after the first round (e.g. Rowe et al., 1991; Woudenberg, 1991), we opt for a multi-round Delphi study. One of the difficulties of multi-round Delphi studies is a potential low response rate, which is often caused by an increasing number of rounds and a perceived excessive survey complexity and length (Spickermann et al., 2014). Hence, we chose to conduct two rounds of Delphi with the goal of minimizing fatigue among panelists, whilst providing panelists the opportunity to reevaluate their opinions, and yielding an as high as possible response rate and validity of results (Mitchell, 1991). Each round is aimed to be completed within 30 min or less. Additionally, for validity purposes, a maximum of 45 days for the entire Delphi study and at least 12 panel responses per round are aimed for, by which the guidelines from the Delphi literature are adhered to (e.g. Enserink et al., 2010; Hsu & Sandford, 2007; Mitchell, 1991).

Altogether, 78 qualified experts and potential panelists are identified as having substantial knowledge on port development and/or PI, and are approached to conduct the survey. 33 are from research institutions, while the remaining 45 are from industry. The majority of the potential panelists are from Europe (72), from both research institutions (27) and industry (45). The other 6 candidates, all from research institutions, are from North America (5 from the USA and 1 from Canada). 25 members from the ALICE-initiative are identified within the European group, of which 20 belonged to industry while the remaining 5 belong to research institutions. We identify and evaluate these experts through their scientific publications and contributions to the development of the PI (e.g. EC's ETP ALICE and SENSE), and/or function and track record in the maritime port industry. Again, by including both academic and industry experts, we aim to obtain more balanced observations, results and implications from both a practical and theoretical perspective. Additionally, since the field of PI is still at a research stage and not yet fully implemented in practice, we need to know about the opinion of researchers, which is also why we have collected data from both groups.

During both online Delphi survey rounds, panelists are asked to assess the evolution level that each PI Dimension would reach on the five-point categorical scale of the PI PF for each contextual scenario, for the years 2030 and 2040. This time horizon with the intermediate year of 2030 is chosen, firstly, to provide panelists ample room to think creatively (Von der Gracht & Darkow, 2010), and secondly, to allow a visualization of a non-linear path, starting from the present.

After each round, an analysis on descriptive statistics is conducted and presented to the panelists. By means of such an analysis, we check for consensus, outliers and potential misunderstandings (Von der Gracht & Darkow, 2010). The statistics included the *interquartile range (IQR)*, *mean, median,* and *standard deviation (SD)*. The IQR is a measure of dispersion for the median and comprises the middle 50 % of the observations (Sekaran & Bougie, 2016). Literature provides a respective consensus criterion of an IQR of 2 or less on a 10-point scale (e.g. De Vet et al., 2005; Hahn & Rayens, 1999). In our case, however, since we are using the 5-point categorical scale of the PI PF, we adopt a respective consensus criterion of an IQR of 1 or less. An IQR of less than 1 reflects that more than 50 % of all opinions fall within 1 point on the scale.

Taking into account that a majority of the potential panelists are located apart, an online survey platform is chosen for the Delphi study. The platform *Typeform* is found to be a user-friendly and effective online tool to conduct the Delphi study with. Prior to taking the survey, each potential panelist, receives a description of the research that includes the purpose of the research and Delphi, and an explanation on the manner in which the contextual scenarios were developed and the PI PF was constructed. Furthermore, for reasons of anonymity, panelists do not have to provide their personal information, and therefore, all answers are considered to be equal in weight. For an impression of the online Delphi survey setup, we refer to Appendix C.

4. PI Port Framework (PI PF) & Contextual scenarios

In this section, we consecutively present the PI PF and the contextual scenarios.

4.1. PI Port Framework (PI PF)

For the construction of the PI PF, the first step is the establishment of the main *PI Dimensions*. These dimensions represent the main elements of the PI that evolve over time. Here, literature review and expert interviews were used. Although different levels of abstraction were found in both literature and expert interviews, we defined three distinct PI Dimensions that capture the general idea of the PI as portrayed by Montreuil (2011), Montreuil et al. (2013), and Treiblmaier et al. (2020), among others. The three PI Dimensions that we defined, which are collectively exhaustive and mutually exclusive, are the following:

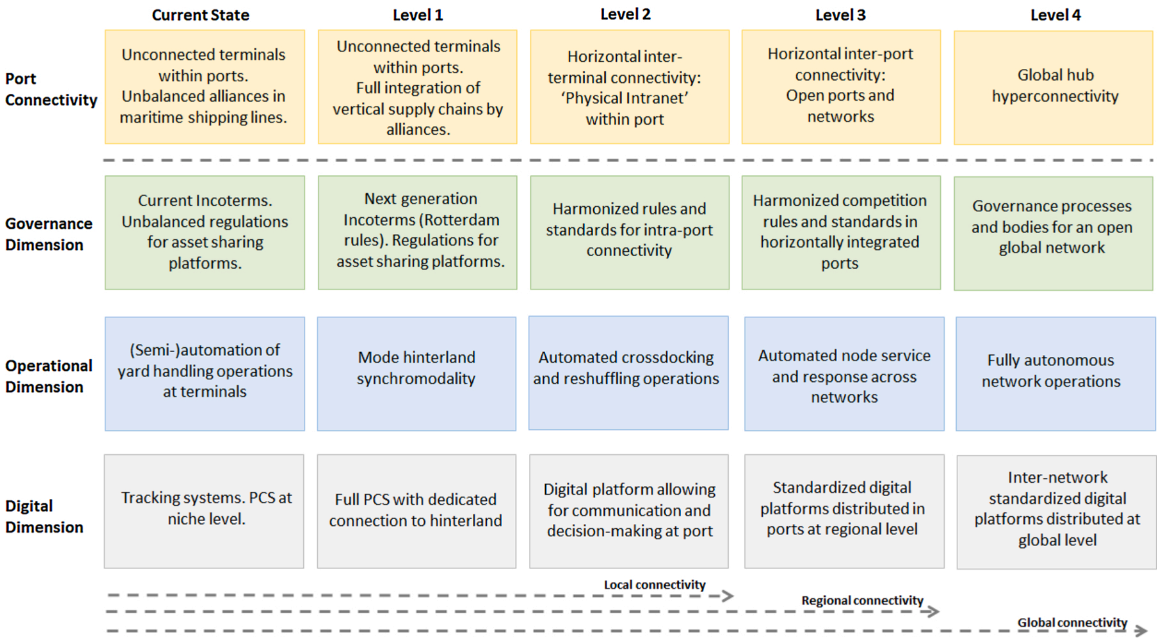

Fig. 2. PI Port Framework (PI PF).

- *Governance Dimension* refers to the set of rules and protocols for a cooperative, safe and reliable PI network and environment;
- *Operational Dimension* refers to the manner in which physical transport operations are executed, and the manner in which the different elements in the transport network (e.g. containers, hubs, warehouses, vehicles, handling equipment) are connected and operated; and
- *Digital Dimension* refers to the digital interconnectedness of the different actors in the logistics network. This allows actors to communicate, share information, and make smart decisions for an optimized transport network.

In the next step of the construction of the PI PF, inspired by the PI Generations approach from the SENSE project (ALICE-ETP, 2020) and the Digital Maturity Model proposed by Port of Rotterdam (2020), an evolutionary PI PF was developed. The framework, presented in Fig. 2, captures how maritime ports as nodes in FTL networks are connected to and evolve in the context of the PI and its respective PI Dimensions.

The *Port Connectivity* layer shows how ports evolve from their *Current State* into *Level 1*, reach *local connectivity* by *Level 2*, *regional connectivity* by *Level 3*, and *global hub hyperconnectivity* by *Level 4*. This layer serves as a function of the (development of the) underlying PI Dimensions, and reflects the degree to which ports are connected internally and externally to the logistics network. It only "advances" into the next level if all three underlying dimensions have. The current state is characterized by unconnected terminals within ports and unbalanced alliances. The first step is made into Level 1, where the separate port terminals remain unconnected, however, where also, in line with current trends, vertical integration from the perspective of the shipping lines is taking place (Parola et al., 2015). In Level 2, ports could be operating in a context that can be referred to as a *Physical Intranet*, which reflects the situation where terminals inside ports have become open, connected, and now also horizontally collaborative. Next, in Level 3, in addition to connected terminals inside the port, ports within the same region (e.g. Hamburg – Le Havre region) have become open, connected and horizontally collaborative (Lind et al., 2021). Finally, Level 4 represents the final stage of the PI PF, where global hub hyperconnectivity has been reached. Hyperconnectivity, here, refers to the highest level of digital and physical connectivity within a network (WEF-BCG, 2014). This final stage of the PI PF can be regarded as the stage where the PI has been implemented in the maritime freight transport system. By showing an evolutionary path, the proposed framework also breaks the misconception that there is a binary state in which the PI exists or not. Instead, the individual layers of the PI Dimensions and the port connectivity layer show that this is a continuous and gradual process.

4.2. *Contextual scenarios*

Through a literature review and expert interviews (see Appendix A for the interview setup), 31 contextual factors, which could influence the global FTL system (e.g. economic growth, automation, big data, Internet of Things (IoT), artificial intelligence (AI), trade agreements, migration flows, cooperative models), are identified and clustered into seven driving forces: (1) *Global Institutional Integration*; (2) *Flow Patterns*; (3) *Climate Change*; (4) *Technological Innovations*; (5) *Regulatory Frameworks*; (6) *Business Models*; and (7) *Demographic Changes*. In establishing the driving forces, we took into account that they should, at least to a large extent, be able to develop themselves independently of the development of other driving forces.

Table 1
Contextual scenarios with respective (directions of) driving forces.

	Global Institutional Integration	Regulatory Frameworks
Scenario 1	(+) Globalization	(+) Rapidly adapting regulatory framework
Scenario 2	(+) Globalization	(−) Slowly adapting regulatory framework
Scenario 3	(−) Protectionism	(+) Rapidly adapting regulatory framework
Scenario 4	(−) Protectionism	(−) Slowly adapting regulatory framework

Table 2
Delphi statistics as indication of consensus among experts between both rounds.

	Round 1 (n = 24)			Round 2 (n = 20)			
	ART: 14.36 min			ART: 14.33 min			
	Median	IQR	SD	Median	IQR	SD	Δ*SD*
Scenario 1							
Governance (2030)	2	0	0.88	2	1	0.60	−31.90 %
Governance (2040)	3	0.5	0.82	3	0.5	0.83	1.60 %
Operational (2030)	2	0.5	0.72	2	0	0.59	−18.30 %
Operational (2040)	3	0	0.68	3	0	0.74	9.50 %
Digital (2030)	2	1	0.89	2	1	0.46	−48.40 %
Digital (2040)	4	1	0.85	4	1	0.91	7.00 %
Scenario 2							
Governance (2030)	1	1.5	0.83	1	1	0.71	−15.00 %
Governance (2040)	2	2	0.84	2	1	0.79	−5.80 %
Operational (2030)	2	1	0.88	2	0	0.57	−34.80 %
Operational (2040)	3	1	0.89	3	1	0.67	−24.70 %
Digital (2030)	2	1	0.88	2	0	0.45	−49.10 %
Digital (2040)	3	1	0.91	3	1	0.86	−5.70 %
Scenario 3							
Governance (2030)	1	2	0.87	1	1	0.77	−11.30 %
Governance (2040)	2	2	0.93	2	1	0.67	−27.60 %
Operational (2030)	1.5	1	0.82	2	1	0.74	−9.30 %
Operational (2040)	2	1	0.75	2	0.5	0.77	3.90 %
Digital (2030)	2	1	0.85	2	0	0.63	−25.60 %
Digital (2040)	3	1	0.61	3	1	0.66	8.60 %
Scenario 4							
Governance (2030)	1	2	0.81	0	1	0.88	−1.50 %
Governance (2040)	2	1	0.82	1	1	0.60	−26.50 %
Operational (2030)	1	1	0.89	1	1	0.68	−23.70 %
Operational (2040)	2	1.5	0.91	2	1	0.70	−23.20 %
Digital (2030)	1	1	0.75	1	1	0.62	−16.50 %
Digital (2040)	2	1	0.91	2	1	0.71	−22.20 %

n: number of respondents.
ART: Average Response Time.
SD: Standard Deviation.
IQR: Interquartile Range.
Median: 0 = Current Situation; 1 = Level 1; 2 = Level 2; 3 = Level 3; 4 = Level 4.

Following the scenario logic approach, as developed by Enserink et al. (2010) and explained in Section 3, the combination of the opposing developments of the driving forces yields the contextual scenarios. Using this approach, selecting two driving forces yields four contextual scenarios, which is in line with our initial aim of between three and eight scenarios. Therefore, the two driving forces were selected with the highest level of uncertainty and impact on the FTL system. We found that *Global Institutional Integration* and *Regulatory Frameworks* have the highest level uncertainty and impact (e.g. Parola et al., 2017; Taneja et al., 2010; Zhang et al., 2018). Although it might seem that these two driving forces influence each other, with the framework founded on the economics of institutions from Williamson (1998) in mind, we argue that their developments, since they evolve in different time spaces, are independent from one another.

Global Institutional Integration could develop into a direction towards increased globalization (+), or into a global environment of high protectionism between major (regional) power blocks (−). Regarding Regulatory Frameworks, the focus was narrowed down to either enabling regulatory frameworks that adapt to market developments rapidly (+), or slowly adapting regulatory frameworks that cause delays in market developments (−). The four scenarios with respective driving forces and their directions are shown in Table 1. While acknowledging that four scenarios might not capture the full breath of uncertainty about the future, a smaller set of scenarios does allow for more meaningful and concrete recommendations and is in line with previously conducted transport futures studies (e.g. Bradfield et al., 2005; Melander, 2018; Tuominen et al., 2014).

Table 3
Summary of evolution levels of the PI Dimensions and the Port Connectivity with respect to the mean and median.

		Mean				Median			
		Governance	*Operational*	*Digital*	**Port Connectivity**	*Governance*	*Operational*	*Digital*	**Port Connectivity**
PI Port Development Path 1	2030	1.80	2.05	2.33	**1.80**	2	2	2	**2**
	2040	2.75	2.95	3.35	**2.75**	3	3	4	**3**
PI Port Development Path 2	2030	1.00	1.65	2.00	**1.00**	1	2	2	**1**
	2040	1.65	2.45	2.60	**1.65**	2	3	3	**2**
PI Port Development Path 3	2030	0.90	1.55	2.00	**0.90**	1	2	2	**1**
	2040	1.50	2.00	2.60	**1.50**	2	2	3	**2**
PI Port Development Path 4	2030	0.60	1.20	1.25	**0.60**	0	1	1	**0**
	2040	1.20	1.75	2.00	**1.20**	1	2	2	**1**

5. Results

In this section, the obtained results from the *online Delphi survey* with respective feedback from the panelists are presented and discussed. Additionally, the obtained results are translated into *PI PDPs*.

5.1. Results of the online Delphi survey

Table 2 summarizes the most relevant Delphi study statistics for each of the three PI Dimensions (governance, operational, and digital) in each of the four contextual scenarios, as explained in more detail in Section 4, for both the years 2030 and 2040.

Out of the 78 potential panelists that were invited to participate in the Delphi, 24 actually participated in the first round, while, after 4 respondents from the first round dropped out, a remaining 20 participated in the second round. Hence, the response rate of the first round was 31 %, while the response rate of the second round was 26 %. On average, over both rounds, it took the panelists less than 15 min to complete the online Delphi survey.

In the statistics of round 1, still 6 cases of an IQR of higher than 1 can be identified. 5 out of these 6 are found in the *GovernanceDimension*, indicating that, initially, the lowest consensus is found here. However, the statistics of round 2 show zero cases with an IQR of higher than 1.

The SD decreased in 19 out of the total 24 cases, indicating that the convergence of panelists' opinions increased in the vast majority over the two rounds. The largest increase in convergence was in Digital (2030) in Scenario 1, with a reduction in SD of more than 48 %. Although all IQRs remained identical or decreased over the two rounds, increases in SDs, i.e. decreases in convergences, albeit small (highest of 9.5 % in Operational (2040) in Scenario 1), can be observed for all three PI Dimensions, however, only in the year 2040. Experts could have been more influenced in their initial decision for year 2030 than for the year 2040, a point where experts might have had a stronger opinion. This could be explained by "anchoring" effects, a common bias in surveys (Kahneman, 2011)

Overall, firstly, from the statistics, we can conclude that consensus among panelists has increasingly been built over the two rounds, which is fully in line with the fundamental rational of the Delphi method – increasing consensus over multiple rounds. Secondly, keeping in mind the earlier adopted consensus criterion of an IQR of 1 or less, we can conclude that, in all cases, desired level of consensus has been met.

5.2. Feedback from panelists

Out of the 24 panelists that participated in the Delphi survey, 11 gave feedback on the proposed PI PF with comments mainly on the evolution levels. At a first instance, one of the experts suggests that "sometimes it is easier to reach Level 2 (connect terminals inside the port) than Level 1 (integrate supply chains)". Similarly, within the *Operational Dimension*, another expert shares the idea that "cross-docking and (re)positioning operations might occur earlier than actual operational synchromodality". Secondly, the framework is built to use as input for a Delphi, assuming that the three dimensions are independent from each other. Nevertheless, one of the panelists argued that there indeed is a dependency between the three dimensions. Thirdly, although we did take into account the data and information element during the development of the PI Dimensions, one of the panelists notes that we emphasize too much on the FTL network perspective, while in his opinion the data perspective should be more dominant in the framework. Fourthly, two panelists share the opinion that the framework could be considered incomplete, suggesting that "additional evolution levels between levels (e.g. 3 and 4) would have been useful".

5.3. PI Port Development Paths (PI PDPs)

Next, the outcomes of the Delphi study are used to generate a set of PI PDPs that shows the possible evolution of current ports towards the PI. For each of the four contextual scenarios (shown in Table 1), the port evolution levels that the three PI Dimensions of the PI PF reach in Round 2 of the Delphi, are summarized into Table 3, both for the year 2030 and 2040. In addition to the three PI Dimensions, the Port Connectivity layer is included in this table. The level of Port Connectivity, as also explained in Section 3, is derived by applying a minimization rule to the three PI Dimensions at a specific point in time. The PI PDPs are then created based on

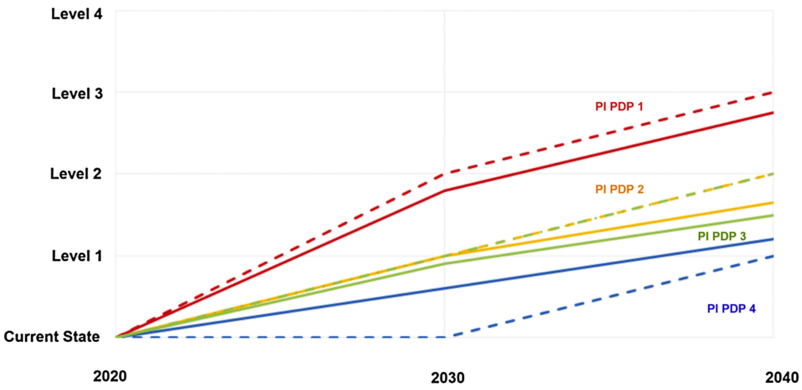

Fig. 3. PI Port Development Paths (PI PDPs) – Mean and median in continuous and dashed lines, respectively.

the Port Connectivity levels, for each contextual scenario, starting at the Current State until 2040. This is done for both the mean and the median, and hence, two PI PDPs for each contextual scenario, as also shown in Table 3. From both the mean and median perspective, it can be observed that the highest evolution levels are reached in PI PDP 1, while PI PDP 4 has the lowest evolution levels, and PI PDP 2 and 3 are similarly in between. In a similar fashion, from the perspective of the three PI Dimensions, it can be observed that, for all scenarios, the Digital Dimension consequently evolves into the highest levels, while the Governance Dimension reaches the lowest levels, with the Operational Dimension falling in between. Here, a hierarchical order in the proposed PI Dimensions can be identified.

The evolution path of Port Connectivity is visualized using the values of the years 2020, i.e. Current State, 2030, and 2040. The results for all PI PDPs are plotted in Fig. 3, with continuous lines representing the mean and dashed lines representing the median. The categorical levels of the PI PF are represented in the left hand side of the graph. The following sections reflect on the different PI PDPs. Albeit different contextual scenarios, PI PDP 2 and 3 are discussed together, given the similarities in their evolutions.

The first contextual scenario is dominated by favorable global institutional integration, where the rise of democracies expands to developing countries by 2040. In line herewith, major power blocks, such as USA, China, and the European Union are able to set up regulatory frameworks that could rapidly adapt to market changes, leading to significant technological adoptions, while simultaneously opening room for new cooperative business models. This optimistic contextual environment results in the most rapid development in the evolution levels of the all three PI Dimensions. From the Port Connectivity layer perspective, the median reaches Level 2 in the year 2030, which means achieving the so-called Physical Intranet of the entire port community from the PI PF, presented in Fig. 2. This means that port terminals (e.g. ECT, DP World, APM Terminals) are horizontally collaborating within the port. Harmonized rules and standards are set in place, automation is highly dominant within in the port, and one system is able to coordinate operations and make decisions on behalf of all relevant port stakeholders, including authorities, such as customs, as well as in- and outbound modes of transportation are connected within the port area. For the year 2040, the median reaches Level 3, which means that connectivity of terminalsgo beyond the boundaries of the port itself, reaching other competing ports within the region, such as the Hamburg-Le Havre region. This could be seen as a form of the PI at a regional level.

The mean suggests a slightly lower evolution, with the Physical Intranet well under its way for the year 2030. This could translate to some stakeholders, from operating companies to governing bodies, such as customs, or the PA itself still not being part, however, taking measures to become part of the intra-port connectivity. Similarly, for the year 2040, few port terminal operators are still to join the regional PI.

Both contextual scenarios 2 and 3 had opposing combination of driving forces (see Table 1). Scenario 2 is dominated by a favorable globalization context, yet with slow regulatory frameworks lagging behind market developments, which would hinder the adoption of new technologies the ease of adoption of cooperative (business) models. The third scenario is in turn marked by a highly protectionist environment at a global level, while regional blocks such as the North America, South East Asia, and the EU had been able to separately set up regulatory frameworks that could quickly adapt to market changes.

The resulting PI PDPs 2 and 3, which lie in between the two opposing PI PDPs 1 and 4, evolve in similar ways. In fact, the median for both PI PDPs are identical during the entire time period considered, evolving to Level 1 and Level 2 for the years 2030 and 2040, respectively. This means that full integration of supply chains is achieved by global alliances by 2030, and terminals become open by the year 2040, thus reaching the Physical Intranet at the port level. When the mean is used instead, PI PDP 2 evolves slightly faster throughout the entire period than PI PDP 3. Yet, for both scenarios, both stay somewhere between Level 1 and Level 2 for the year 2040 (2,65 and 2,50 respectively), suggesting that some terminals are still not connected with others at the port level.

On the opposite end is contextual scenario 4, which involves a challenging global setting of high protectionism between major power blocks and slow regulatory frameworks lagging behind market developments. From the perspective of the level of Port Connectivity for PI PDP 4, the median stagnates at the Current State for the year 2030 and evolves to Level 1 only for the year 2040. The mean suggests that the global alliances steadily continue their current trend towards a full integration of their dedicated (vertical) supply chains since the current year until 2040. By this point in time, individual companies also improve their dedicated operations, and ports implement Port Management Systems and Port Community Systems (PCS) that allow for communication between the different parties and reduce redundant paperwork. Yet, flexible horizontal cooperation is still under development at the port community level, mainly due to a lack of harmonized rules and standards that could allow for intra-port connectivity. The Physical Intranet within the port domain is still under way for the horizon year 2040.

6. Discussion and validation

To discuss and validate the obtained final results, the Delphi statistics and PI PDPs, we conducted a series of semi-structured expert interviews. Quotes in this section are from the respective expert validation interviewees, as also listed in Section 3.2.

The general feedback from the experts was that, overall, the obtained statistical results and PI PDPs are plausible from researchers' and practitioners' perspectives. In line with the constructed PI PF and obtained results from the Delphi survey, it was confirmed that "currently the internal port stakeholders are not very well digitally connected". In addition, although there is a widespread consensus that ports have the potential of becoming future information hubs with real-time decision-making capabilities to support the orchestration of supply chains, it was also argued that "currently there is a lack in standardization of data and information, information systems, and protocols within port systems".

From the direction that the interviews took, it became clear that the current focus in improvement practices for port systems is very much on the *Digital Dimension*, as defined in the PI PF. "As being a frontrunner in terms of digital capabilities within port communities, a PA could play an advisory role towards other stakeholders, such as the Digital Container Shipping Association (DCSA) that aims to establish standards for a common technology foundation to enable global collaboration. A PA could also take the lead in developing a neutral local information platform (e.g. PCS) that further connects to neutral regional and global information platforms". Regional and global PCS could be developed in coordination with, and by the lead of, the International Port Community Systems Association (IPCSA, 2021). Considering data sharing, influential ports could act as a first mover in the chain with the goal to convince other stakeholders to follow their example, with the goal of creating network effects and trust. As also shown in Fig. 2, "the coordination and communication (by means of PCS) should reach beyond boundaries of the port itself and extend into both the fore- and hinterland". Hence, in the development of these systems, also shippers, shipping lines, LSPs, and governmental institutions should be included.

Regarding the *Governance Dimension*, "globally leading PAs could lead the way in developing (global) community and industry standards in integrated ports". In a similar fashion, PAs could play an active advisory role to (international) governmental institutions, such as the International Maritime Organization (IMO), by evaluating and monitoring the implementation of new standards, regulations, and harmonized rules, such as the upcoming Rotterdam Rules. Keeping stakeholders informed could allow a parallel and joint implementation, internationally. Similarly, with the Consortia Block Exemption Regulation (CBER), PAs could either lobby in favor of its extension, or, in coordination with shipping lines, propose a more flexible version of the current CBER, while still being in compliance with Article 101 of the Treaty of the Functioning of the European Union (TFEU).

Regarding the *Operational Dimension*, PAs could make sure that they are automated and later autonomous, crossdocking and (re) positioning operations and systems are up to the standards of the PI (Fahim, An et al., 2021). Here, investments should be made by both PAs and terminal operators into updating existing and developing new facilities. Also, shippers, shipping lines, and LSPs could contribute to the Operational Dimension by taking a lead in the introduction of standardized solutions, such as the modular PI containers. Another international collaborative initiative that aims to increase the efficiency of shipping operations, by means of developing standards, is the International Taskforce Port Call Optimization (ITPCO)

Altogether, the obtained results were considered to be realistic and plausible, and therefore, positively validated by the experts. The outcome of the PI PDPs from the Delphi study can be a starting point for PAs to consider the influence of the PI in maritime freight transport systems. Assuming that the goal of PAs is to maximize the level of Port Connectivity from the PI PF for the projected years, their current aim should be to develop a long term strategy in accordance with this goal. Although the results have shown that the Governance Dimension can be considered as a bottleneck, the strategy should include measures and actions that also target the Operational and Digital Dimensions.

7. Conclusions and future research

The purpose of this paper was to address the literature gap around the future of maritime ports in and towards the PI, uncovering the plausible developments paths of maritime ports. By conducting a contextual scenario analysis, constructing a PI PF, and executing a two-round Delphi study, a set of PI PDPs that showed the potential evolution of ports towards PI Ports was generated.

On the basis of the obtained results, several conclusions can be drawn. Firstly, despite the PI's components stemming from technological innovation, the PI PDPs confirmed that the Governance Dimension is most likely to become a bottleneck, and hence, the most critical in terms of port development. Secondly, from the resulting PI PDPs 2 and 3, it seems that panelists, on average, penalized an environment of high protectionism (contextual scenario 3) more than a future with slow regulatory frameworks hindering market developments (contextual scenario 2). Thirdly, under the most optimistic scenario in terms of global institutional integration and regulatory frameworks, the PI in ports as autonomous nodes in the FTL system is achieved on a regional (e.g. European) level at most, equivalent to Level 3. Level 4, which is considered the ultimate stage of the PI, is never reached in any of the four PI PDPs. Here, it must be taken into consideration that we applied a minimization rule to determine the actual level of Port Connectivity. However, even if an alternative compensation rule between the three PI Dimensions (e.g. average of the three) would have been used to determine the level of Port Connectivity, the final stage of global hub hyperconnectivity would still not have been reached. Only, by using the median and a maximization rule, with the Digital Dimension in the lead in PI PDP 1, would Port Connectivity reach the ultimate stage of global hub hyperconnectivity. Hence, the overall conclusion can be drawn that global hub hyperconnectivity among ports, as prescribed by the PI, is unlikely to be reached by 2040. Furthermore, recommendations towards PAs and other supply chain stakeholders have been made regarding the Governance Dimension, Operational Dimension, and Digital Dimension to increase the chances of reaching global hub hyperconnectivity.

As avenues for future research, we propose an estimation of future freight flows within each of the developed contextual scenarios by means of solving a mathematical network design problem. This could enable further quantification of the results obtained in this research. These calculated freight flows would provide insights into the potential threats and opportunities that ports could use as support in their policy formulation. As a potential next step, based on the different contextual scenarios, adaptive policy roadmaps could be designed that focus on the actions and measures to be taken by ports (and other stakeholders) at specified moments in time to maximize their chances of success.

Acknowledgements

This research is funded by NWO (Dutch Research Council), the Port of Rotterdam and Groningen Seaports (grant number NWO-4381525), and is conducted in partnership with the Georgia Institute of Technology and the University of Groningen. The authors would like to sincerely thank all interviewees and panelists for their invaluable contributions. Also, the authors would like to sincerely thank the journal's editor and reviewers for their valuable comments to get to the result of this paper.

Appendix A. Expert interview setup

The Physical Internet (PI) is a novel vision that aims to reshape and improve the efficiency of transport and logistics. An idea of this magnitude is expected to have a profound effect on all actors involved in freight transport systems. With the concept still in early stages, the study of maritime ports in the context of the PI has remained nearly unexplored. *The purpose of this interview is to (1) establish a set of contextual factors that influence the PI (in the context of maritime ports), which can be clustered into driving forces,* and *(2) conceptualize the evolution of maritime ports in the context of the PI by defining its main dimensions.*

A.1 Contextual factors and driving forces

Next, we investigate the *contextual factors* that affect (the development of) the PI, i.e. the PI components, in the context of maritime ports. Contextual factors can be defined as variables that influence the development, performance, and outcome of a system, however, cannot be influenced by the problem owner herself. By means of reviewing the literature, we have identified the contextual factors that

Table A1
Contextual factors.

Contextual factor	Source(s)
Population growth	DHL (2012), Nextnet (2017), Port of Rotterdam (2019a, 2019b) and Snabe and Weinelt (2016)
Economic growth	DHL (2012) and Nextnet (2017)
Urbanization	DHL (2012)
Pollution	DHL (2012) and Nextnet (2017)
Automation	DHL (2012), Hahn (2020), Nextnet (2017), Nowak et al. (2016) and Snabe and Weinelt (2016)
Environmental regulations	DHL (2012) and Snabe and Weinelt (2016)
Belt and Road Initiative	Port of Rotterdam (2019a, 2019b)
Climate change	Nextnet (2017)
Mass individualization	DHL (2012), Nextnet (2017) and Tavasszy (2018)
Migration flows	Nextnet (2017)
Increase of vessel size	Notteboom (2016)
Global monopolistic operators	Nextnet (2017)
Cooperative models	Port of Rotterdam (2019a, 2019b), Snabe and Weinelt (2016) and Tavasszy (2018)
Individualistic models	Nextnet (2017) and Tavasszy (2018)
Innovative business models	Snabe and Weinelt (2016)
Trade agreements	Nextnet (2017) and Tavasszy (2018)
Internet of Things (IoT)	DHL (2012), Hahn (2020), Port of Rotterdam (2019a, 2019b), Snabe and Weinelt (2016) and Tavasszy (2018)
Big Data	DHL (2012), Hahn (2020), Nextnet (2017), Port of Rotterdam (2019a, 2019b) and Tavasszy (2018)
Artificial Intelligence (AI)	DHL (2012), Hahn (2020) and Nextnet (2017)
Drones	Hahn (2020), Nextnet (2017), Snabe and Weinelt (2016) and Tavasszy (2018)
Cybersecurity	Nextnet (2017)
Import tariffs and quotas	Nextnet (2017)
Different tax environments	Nextnet (2017)
National subsidies	Nextnet (2017)
Nearshoring	Port of Rotterdam (2019a, 2019b)
Antitrust policies	Tavasszy (2018)
Labor protection	Snabe and Weinelt (2016)
Depletion of natural resources	Nextnet (2017)
Political union in Europe	Snabe and Weinelt (2016)
Circular economy	Hahn (2020) and Snabe and Weinelt (2016)
3D printing	Hahn (2020), Nextnet (2017) and Snabe and Weinelt (2016)

are tabulated in Table A1. We would like to ask you for your opinion on (the use of) these contextual factors and the way we could cluster them into *driving forces* (e.g. trade patterns, environmental, geopolitical, technological). *What is your opinion of the below list of identified contextual factors and how could we best cluster them into driving forces?*

A.2 PI Port Framework Dimensions

As essential part of our research, we need to conceptualize the evolution of maritime ports in the context of and towards the PI. We do this by conducting a literature review and experts interviews (with you). Through literature review, we found three main *dimensions* in which ports evolve towards the PI. We would like to use these as a base for the first part of our discussion. *What is your opinion of the PI Dimensions that we have so far and what do you think they should be?*

- **Modularity:** One of the core components of the PI. In our case, we take a broad definition, arguing that it does not only encompass the modular PI-containers, but also the encapsulation of all types of goods in them. These are transported and handled in PI vehicles and all sorts of tools which are equipped with handling interface. In order to encapsulate goods into containers, algorithms or protocols are followed.
- **Collaboration:** This component can take a broad definition, but from literature the important notion is *the sharing of resources and assets between the different players and actors in the transport chain*. Digital tools or interfaces can allow different players to publish their available capacity in real time, and therefore, matching a particular demand for resources with their current supply. For a smooth collaboration, however, both need to be standardized at the same level, with the same handling interfaces tailored to handle modular PI-containers. From a business and legal perspective, different rules or protocols need to be followed so that all players benefit from operational and economic transactions.
- **Interconnectivity:** As with the previous, interconnectivity can take a broad meaning. From the publications considered for this research, the most suited definition could be *the connectedness of the different movers, containers, hubs and other players in the logistics network*. Meaning that they can share information, communicate and make decisions automatically with each other so that a more efficient network, from a system perspective rather than at an individual level, can be achieved. Digital interfaces as well as decision algorithms or protocols can help in this endeavor. An example could be the usage of passive RFID tags on PI-containers to facilitate their traceability, where handling tools such as Cranes or Automated Guided Vehicles (AGV) follow a Dynamic Model Predictive Control (DMPC) as the main protocol.

Appendix B. Expert validation interview setup

The Physical Internet (PI) is a novel vision that aims to reshape and improve efficiency of transport and logistics. An idea of this magnitude is expected to have a profound effect on all actors involved in freight transport systems. With the concept still in early stages, the study of maritime ports in the context of the PI has remained nearly unexplored. This research aims to provide insights into the evolution of maritime ports towards the PI.

By means of this interview, we would like to:

- validate the results of our research in terms of the plausibility of the obtained development paths;
- gain insights into (practical) implications for ports (now); and
- gain insights into potential short and long term policy recommendations for ports.

Table B1 summarizes the obtained results from the Delphi study, and presents the evolution level from the PI Port Framework that ports reach in the different PI Port Development Paths (PI PDPs). Values in the left column represent the mean value of the PI Dimensions and "Port Connectivity" from the *Current State* (0) to *Level 4* (4), while the values in the right column represent the median for each of the PI Dimensions in the different years. Fig. B1 is a visualization of Table B1 and shows the potential PI PDPs. I will explain the PI PDPs and their background in more detail. *Would you consider the obtained statistical results from the Delphi and the derived PI PDPs as*

Table B1
Summary of evolution levels of the PI Dimensions and the Port Connectivity with respect to the mean and median.

		Mean				Median			
		Governance	*Operational*	*Digital*	**Port Connectivity**	*Governance*	*Operational*	*Digital*	**Port Connectivity**
PI Port Development Path 1	2030	1.80	2.05	2.33	**1.80**	2	2	2	**2**
	2040	2.75	2.95	3.35	**2.75**	3	3	4	**3**
PI Port Development Path 2	2030	1.00	1.65	2.00	**1.00**	1	2	2	**1**
	2040	1.65	2.45	2.60	**1.65**	2	3	3	**2**
PI Port Development Path 3	2030	0.90	1.55	2.00	**0.90**	1	2	2	**1**
	2040	1.50	2.00	2.60	**1.50**	2	2	3	**2**
PI Port Development Path 4	2030	0.60	1.20	1.25	**0.60**	0	1	1	**0**
	2040	1.20	1.75	2.00	**1.20**	1	2	2	**1**

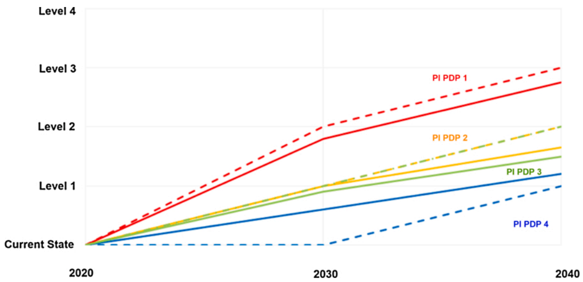

Fig. B1. PI Port Development Paths – Mean and median in continuous and dashed lines, respectively.

realistic and plausible?

Appendix C. Delphi setup

The questions in the online Delphi survey were structured following an IF/THEN rule. By applying this format to the Delphi, all the possible combinations of the selected driving forces (DF_n) can be presented to the experts in a structured way, which can in turn provide their opinion (*THEN*) with respect to the development of each PI Dimension (PI_1, …, PI_n). For our two driving forces, *Global Institutional Integration* and *Regulatory Frameworks,* we yield four contextual scenarios (see Table C1). Fig. C1 shows a screenshot of the actual online Delphi survey and gives an impression of how it was conducted.

Table C1
Input and output of Delphi survey.

Input for panelists		Output from panelists	
IF	Contextual scenario	THEN	PI Port Development Path
DF_1 is HIGH and DF_2 is HIGH	1	PI_1 is …, PI_2 is … and PI_n is …	1
DF_1 is HIGH and DF_2 is LOW	2	PI_1 is …, PI_2 is … and PI_n is …	2
DF_1 is LOW and DF_2 is HIGH	3	PI_1 is …, PI_2 is … and PI_n is …	3
DF_1 is LOW and DF_2 is LOW	4	PI_1 is …, PI_2 is … and PI_n is …	4

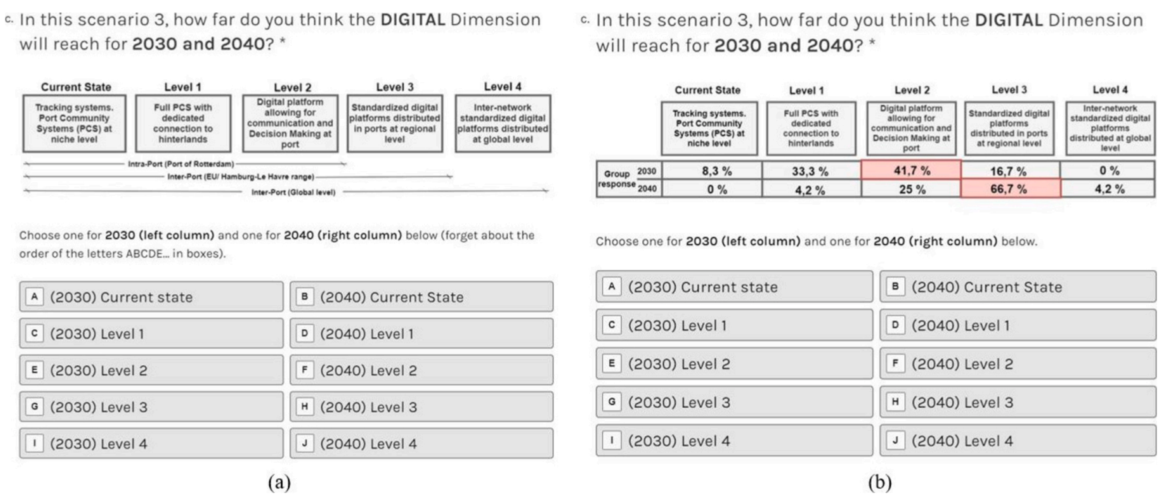

Fig. C1. Screenshots of the interface of the online Delphi survey for Round 1 (a) and Round 2 (b). Online Tool: typeform®.

Round 1 was structured as follows:

1 A first welcome slide with the reminder that the survey would take between 15 and 25 min.
2 An explanation of the purpose of the survey and the PI Port framework was presented.
3 A description of the first contextual scenario which was followed by 3 slides, each with a multiple-choice question for each of the 3 dimensions of the PI Port framework. Experts had to choose the level (from *Current State* to *Level 4*) that each dimension would

reach in the years 2030 and 2040. This process was repeated for all other scenarios, a total of 12 slides (3 dimensions x 4 scenarios) to select 24 levels of development in total (2030 and 2040). Panelists were not asked to argument each of their answers.

4 A closing slide thanking the experts for participating in the survey. At this point, we reminded the participants that a second and last round would follow within the next weeks.

Round 2 kept a similar structure as Round 1. For each multiple-choice question regarding the level that each dimension would reach for 2030 and 2040 depending on a given scenario, the average response from the previous round was provided. This was done in line with the fundamental rational of the Delphi method, with the aim that the results of the responses of the first round would lead to a higher consensus among the experts' opinions in the second round.

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