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The Future of Ports in the Physical Internet

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The Future of Ports in the Physical Internet

Dissertation

for the purpose of obtaining the degree of doctor
from the Delft University of Technology,
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Chair of the Board for Doctorates,
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by

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Preface

This Ph.D. dissertation is the result of several years of research on the fascinating topic of the future of maritime ports in the Physical Internet. I would like to use this preface to thank the people that have supported me throughout my Ph.D. journey.
A journey that allowed me to meet and become friends with extraordinary people.
A journey that allowed me to work with some of the most capable.
A journey that forced me to make my own decisions.
A journey that taught me about myself and others.
A journey that made me travel far and wide.
A journey that made me laugh and cry.
A journey that made me grow.
Hopefully, into a better man.

I would like to start by expressing my sincerest gratitude to Prof.dr.ir. Lori Tavasszy. You granted me the opportunity to have this once-in-a-lifetime experience, and you guided me towards a successful finish. Over the years, I have learned a great many things from you, among which, how to remain pragmatic in a highly complex environment, and how to carefully manage the process and its stakeholders whilst keeping the end in mind. I always felt that you were greatly interested in my research, and I will always remember our, mostly digital and relaxed, late afternoon chats with the image and sound of your chickens in your backyard. Thank you for your patience, enthusiasm, guidance, and support from the beginning till the end.

I would like to express my sincerest gratitude to Dr. Jafar Rezaei. Our history dates back from before this Ph.D. journey started. Over the years, I have had the pleasure of seeing you grow as not only a terrific scientist, but also as a capable leader. Not a problem is too hard to solve for you, while you make it all look so easy. With the highest of expectations and with much excitement, I look forward to what is yet to come from you. I have always enjoyed and learned much from our both on- and off-topic conversations. Thank you for being a continuous source of guidance, wisdom, and inspiration.

I would like to express my sincerest gratitude to Prof.dr. Benoit Montreuil. Thank you for hosting me during my research visit at Georgia Tech. This was one of the definite highlights of my Ph.D. journey, a truly unforgettable experience. Your energy, enthusiasm, and passion for the Physical Internet had a contagious effect with regard to my own interest and efforts. Thanks to you, I, among many other things, now better understand the overall meaning and importance of (having) a strong and meaningful mission and vision. Thank you for your contagious energy, guidance, and support ever since my first visit to the Physical Internet Center.

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Patrick Fahim
April, 2022
Amsterdam

Contents

1 Introduction

1.1 Background: Ports and the Physical Internet (PI)

Freight transport and logistics (FTL) produce around 15% of the world's GDP and account for approximately 10% of finished product costs on average (Mervis, 2014). However, through its contribution to the carbon footprint and traffic congestion, today's FTL operations are often considered to be non-sustainable from an economic, environmental, and societal perspective (Montreuil, 2011). Transportation marks its presence with over 30% of the global carbon emissions (IEA, 2019). Additionally, as demonstrated by regular disruptions and the resulting shock-effects on international trade and manufacturing, the global FTL system suffers from vulnerabilities and lack of resilience (Dickens et al., 2021).

In addition to being critical components in the FTL system, maritime ports function as facilitators of international trade, through which they contribute to the economic development of countries and regions (Arvis et al., 2018). Over centuries, maritime ports have evolved from simple gateways between land and sea into highly complex systems with a large and diverse number of stakeholders being involved, and various types of services being offered (see Figure 1.1). This has caused maritime ports not only to function as (transshipment) hubs in FTL networks, but also a location where industrial and value-added services take place. Haraldson et al. (2021) argue that ports can be considered as dynamic organic systems within both national socio-economic-political and globalized economic systems, where ports need to continuously adapt to their external environment by changing economic and trading patterns, new technologies, legislation, and port governance systems (Nijdam & Van der Horst, 2017).

An innovation that is expected to impact the current economic and trading patterns, technologies, legislation, and governance systems, is the Physical Internet (PI). The term PI was, for the first time, introduced in the domain of transport and logistics in June 2006 on the cover of The Economist (Markillie, 2006). Later, in their seminal paper, Montreuil et al. (2013) positioned the PI as an all-encompassing vision for a future FTL system that transforms "the way physical objects are moved, stored, realized, supplied and used across the world", aiming towards greater economic, environmental, and societal efficiency and sustainability. By analogy with the digital internet (DI), physical shipments are encapsulated into multi-level modular containers and sent through an open hyperconnected network of logistics networks to their final destinations (Ballot et al., 2014). Montreuil (2020) defined the PI as "a hyperconnected global logistics system enabling seamless open asset sharing and flow consolidation through standardized encapsulation, modularization, protocols and interfaces to improve the efficiency and sustainability of serving humanity's demand for physical objects". Additionally, Montreuil (2020) identified eight essential Building Blocks for the PI: (1) Unified Set of Standard Modular

Logistics Containers; (2) Containerized Logistics Equipment and Technology; (3) Standard Logistics Protocols; (4) Certified Open Logistics Facilities and Ways; (5) Global Logistics Monitoring System; (6) Open Logistics Decisional & Transactional Platforms; (7) Smart Data-Driven Analytics; and (8) Certified Open Logistics Service Providers.

A paradigm-changing vision of this magnitude is expected to have a profound impact on all actors of the FTL system. With 80% of the 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. In addition, since ports are asset heavy and highly capital intensive (Rodrigue, 2010), understanding uncertainties in the development of the FTL system is crucial for ports to determine appropriate strategies and allocate investments. Albeit recognized as a promising vision by both academia and industry with a growing interest and number of (scientific) publications, the development towards the PI simultaneously creates much uncertainty for today’s stakeholders of the FTL system and requires collaborative research initiatives by academic, industry, and governmental institutions. Nevertheless, the topic of maritime ports in the context of the PI so far has been unexplored. As a result, ports currently lack substantive knowledge on the way the global FTL system will develop towards the PI, and the way ports could contribute to and anticipate on these developments. Although our objective is not to define nor design the sixth generation port, through the transformation of the current FTL system towards the PI, we will be investigating how ports could co-evolve beyond the fifth generation.

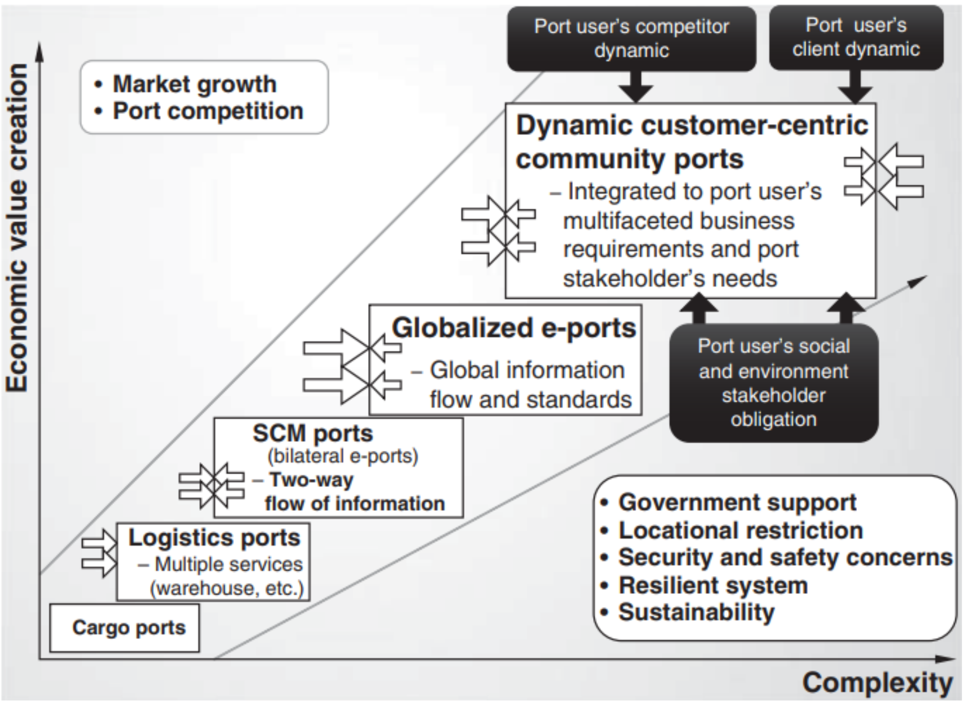

Figure 1.1: *Evolution of ports (adopted from: Lee and Lam, 2016)*

The scientific contribution of this research is to conceptually and empirically explore the future of maritime ports towards the PI. The main practical question of relevance for current port practitioners is: “which hubs will emerge as winners in the PI and which ones will become peripheral?”. Over the long-term, for the continuity of ports, it is important to gain insight into the possible consequences of a local, regional and global PI rollout, and to formulate robust strategies that will allow ports to secure a position as a strategic hub in a future PI network. We investigate this question from three key perspectives: (1) scenarios for the development of the

FTL system towards the PI; (2) requirements for ports to be attractive for its users in the PI; and (3) robust policy areas that answer to these scenarios and requirements.

1.2 Research questions

We formulate the main research question (RQ) as follows:
How can maritime ports anticipate on the developments towards the Physical Internet?

Since the maritime transport system can be expected to be significantly affected by the uncertain developments towards a fully functioning global PI, understanding these uncertainties is crucial for ports to determine appropriate strategies and allocate investments. By identifying the plausible development directions, we conceptually and empirically explore these uncertainties. Therefore, to be able to answer the main RQ, we formulate the following sub-RQs:

RQ1: What are plausible development paths for the evolution of maritime ports towards the Physical Internet?
The development towards the PI is expected to have a profound impact on all actors of the FTL system. Simultaneously, the development towards the PI creates much uncertainty for today's FTL system's stakeholders, because of which the continuation of the role and function of current ports become uncertain and path-dependent. For instance, the way governance, digital, and operational systems will develop towards the PI are uncertain and not trivial. Failure in properly understanding and anticipating on these developments can result in negative consequences, not just for the port itself, but also for the local, national and regional economy (Halim et al., 2016). A common practice to deal with uncertainty and path dependency is scenario development (Melander, 2018). Through developing scenarios, the primary objective of this part of the research is to generate a set of development paths for the evolution of maritime ports towards the PI.

RQ2: How will port users in the Physical Internet evaluate port performance and select the most suitable port?
While current port users are primarily represented by shippers, shipping lines, and logistics service providers (LSPs) (Rezaei et al., 2019), we are interested in a similar differentiation in decision-making perspectives but then in the context of the PI. The automated PI routing protocol will require a different distribution of decisions over actors, where the envisioned intelligent agents, i.e., autonomous containers and vessels, will replace current port users as decision-makers (DMs) for port performance evaluation and selection. The analysis of port performance evaluation and selection has important implications for a port's policy formulation and investment decisions (Martinez Moya & Feo Valero, 2017). Especially in policymaking under uncertainty, where investments and long-term policies are being evaluated, potential changes in (the valuation of) port performance and selection metrics by its users should be well understood. Within this context, we aim to understand whether any change can be expected in DMs' preferences in port performance criteria.

RQ3: What is the proper arrangement of information flows on shipments and their characteristics, that supports T&T of goods inside a port, within the context of the PI?
To achieve hyperconnectivity in the PI, ports need to be capable to autonomously route shipments of PI containers, based on the availability of appropriate real-time information. Future PI applications will be data-driven and will require strong sensing, communication, data processing, and decision-making capabilities. In the design of intelligent systems, sensing (information handling), which is the focus of this part of the study, comes prior to thinking

(problem notification), and acting (decision-making). In PI applications, we consider sensing as the process of creating increased visibility by means of enhanced track-and-trace (T&T) systems. PI ports will need to be able to process information on an individual shipment level to facilitate optimal (un)loading and (re-)positioning operations of PI containers. Additionally, in the PI, T&T includes the real-time ability to locate every individual PI container with its contents and to provide traceability information (e.g., weight, state, commodity type, estimated arrival and departure times, origin and destination, and environmental conditions) to relevant internal and external entities and actors (Sallez et al., 2016). Today, however, port information systems (ISs) only support T&T at container level, typically 20 and 40 foot containers, and not at the level of underlying shipment units, i.e., PI containers. Hence, if ports choose to keep an essential existence in the future door-to-door PI system, these enhanced T&T capabilities need to be supported by the suitable ISs with respective arrangement of information flows on shipments in information architectures (IAs). The design of an innovative PI T&T IA for ports is what we focus on in this part of the research.

RQ4: What are suitable policy areas for port authorities in the development towards the Physical Internet?
Port authorities (PAs) are the organizations that are responsible for a competitive, sustainable and safe development of maritime ports (Notteboom et al., 2013). They synchronize the interests and actions of public institutions (e.g., national government, local municipality) with the behaviour and strategic intent of private port operators, and their own strategic intent (Van der Lugt et al., 2017). After gaining insights into the potential development paths of maritime ports towards the PI (RQ1) and their respective requirements (RQ2 and RQ3), by means of answering RQ4, we aim to provide PAs with necessary guiding principles for their growth towards the PI, i.e., recommendations on policy areas under the uncertain development and changing environment of the PI.

RQ5: How can managers in the port and maritime industry anticipate on and contribute to the implementation of the PI?
While a vast majority of the current PI literature uses theoretical approaches with a focus on longer term developments, the more practical perspective, and the way current (technological) developments can contribute to the implementation of the PI in the context of maritime ports, have not yet been addressed. As a result, decision-makers in ports, the related industries and in government do not possess sufficient knowledge on how to anticipate on the uncertain development of the PI on the shorter-term. Therefore, we aim to, firstly, identify current (technological) developments that influence and relate to the implementation of the PI in the context of maritime ports, and secondly, provide (port and maritime) DMs with insights into the development of the FTL system towards the PI, what this could potentially mean for them, and how they can contribute to its realization.

1.3 Research approach

This describes the research approach and structure of the thesis. Figure 1.2 visualizes and summarizes the research approach in the shape of an ancient Greek temple structure, and is explained below into more detail. Every part of the structure is connected to one of the RQs from Section 1.2.
As a *foundation* to our research, related to RQ1, we generate scenarios and development paths for the evolution of maritime ports towards the PI. To be able to do so, firstly, a conceptualization in terms of an evolutionary port development framework, which shows the evolution of today's ports into globally hyperconnected PI ports, is constructed. Within this PI

Port Framework, the main dimensions of the PI in relation to ports are identified. Additionally, the framework shows how these dimensions evolve over time and result into local, regional, and global connectivity of ports. Secondly, next to the development of the PI Port Framework, scenario development is conducted to obtain the plausible scenarios under which ports could develop towards the PI. Thirdly, both the constructed PI Port Framework and the obtained scenarios are used as input for the Delphi study, in which the participants evaluate how far ports would be developed within the PI Port Framework under the different scenarios. By means of the results of the Delphi study, the PI port development paths are obtained.

In the *Management* pillar, related to RQ2, we make a first step in the modelling of intelligent agents' preferences in the context of selecting ports in the PI. Decision-making can be complex and dynamic due to the involvement of various stakeholders and many, sometimes conflicting, criteria. An example of conflicting criteria could be costs versus service quality, where normally costs rise when the service quality increases, while the goal often is to keep the costs low and the service quality high. A frequently used approach to analyse port performance and selection is multi-criteria decision analysis (MCDA). We employ the Bayesian best-worst method (BWM), which is a probabilistic variant of BWM (Rezaei, 2015), designed to obtain weights of criteria for a group of DMs (Mohammadi & Rezaei, 2020). In addition to supporting port users to choose the most suitable port, the analysis also provides ports with insight into the preferences of their potential clients. These insights allow ports to better understand how to manage their performance, invest resources, and formulate policies to improve their own competitiveness.

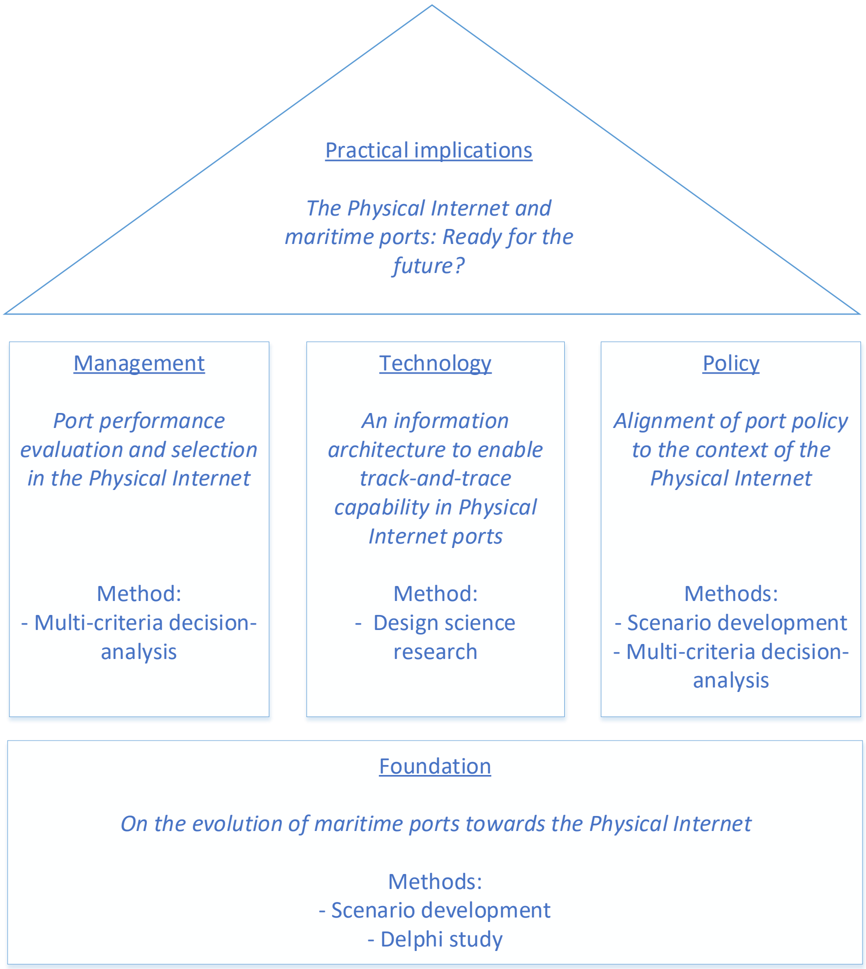

Figure 1.2: *Research structure*

In the *Technology* pillar of our research, related to RQ3, we address the task of re-designing ports' ISs to suit new and required T&T capabilities for ports in the PI. Within an IS, the different aspects of information sharing, including data elements, message formats and communication lines, should be defined in line with the new business objectives, and in a consistent relation to each other. The design of a shared information environment that lives up to these conditions is called an IA. To keep the different aspects of the information tractable, consistent and complete, we use a reference architecture model (RAM) for the IA design. More specifically, we use the Reference Architecture Model for Industry 4.0 (RAMI 4.0) (Adolphs et al., 2015).

Since PAs are required to make decisions about large scale capital intensive projects with an irreversible character which can take many years to implement, policymaking in this context can be considered to be a highly complex task (Parola et al., 2017). A (rapidly) changing environment, such as the FTL developing towards the PI, further increases this complexity. In the *Policy* pillar of our research, related to RQ4, we employ scenario development in combination with MCDA to analyse multiple potential future scenarios with their own respective requirements regarding port performance. We develop a set of policy areas that could help ports to survive and thrive in the uncertain development in the PI.

The roof structure on top of the pillars, related to RQ5, comprises an overview and aims to provide strategic decision-makers in the maritime port industry and in government with insights into the development of the PI on a shorter-term, and how they could anticipate on and contribute to the development of the PI. We use the results of the prior parts of the research to derive *practical implications*, future challenges, and recommendations for practitioners.

1.4 Contributions

1.4.1 Scientific contributions

Since the subject of maritime ports in the context of the PI has been unexplored by researchers, the main scientific contribution of this research is a conceptual and empirical study into the future of maritime ports inside the PI. The contribution is further explained below per chapter and corresponding journal article.

In Chapter 2, there are two main contributions. Firstly, we design an evolutionary port development framework that shows the evolution of a today's maritime port into a PI port. By identifying the main dimensions of the PI in relation to ports, the governance-, operational-, and digital dimension, this PI Port Framework shows how these dimensions evolve over time and result into local, regional, and global connectivity of ports. Secondly, by applying scenario analysis with a Delphi study among port experts, we develop an empirically supported picture of potential development paths for maritime ports in a PI context.

In Chapter 3, we analyse port performance evaluation and selection from the perspective of intelligent agents in the maritime context of the PI. Here, we use insights from the port performance evaluation, port selection, and PI literature to study the combined problem. This is the first study that uses experts to help to assess probable changes in preferences of users in the FTL system in a PI context.

In Chapter 4, we contribute to literature by proposing an IA for maritime PI ports, which has been lacking so far. To tackle this problem, we employ a design science research (DSR) approach, which allows to combine practical relevance and scientific rigor to conduct research in the field of ISs. By means of a tractable and reproducible design case for the T&T capability of maritime ports in a PI context, based on RAMI 4.0, we keep the design rooted in a real-world situation and demonstrate the applicability of the innovative IA through a concrete use case.

Chapter 5 contributes to the port policy and PI literature by identifying suitable PI port policy areas that could help PAs to be attractive to port users towards and in the PI. Furthermore, a methodological contribution is made by combining scenarios for alternative futures with port performance dimensions in a novel multi-criteria, multi-futures port policy design framework. We frame this question for practitioners more broadly in Chapter 6. This can be seen as a contribution to the management literature, drawing together lessons towards the main research question.

Altogether, these results contribute to filling the current research void, addressed by this thesis, about the development of maritime ports towards the PI.

1.4.2 Societal contributions

By looking at the societal relevance of this thesis, it becomes clear how the PI could be used by those who make strategic decisions about technology, engineering and innovation in a port and maritime environment. Although this mostly becomes apparent in Chapter 6, which specifically aims to discuss the relevance of the PI for managers in the port and maritime industry, societal contributions are made throughout every chapter of the thesis.

By means of the PI Port Framework, Chapter 2 shows practitioners and policymakers a multidimensional generational transition from the current state of ports into ports in a fully globally functioning PI in the future. Additionally, by means of the identification of external factors and driving forces that influence the development of ports towards the PI, scenarios and respective potential pathways are constructed, with an emphasis on the development of the governance dimension. Practitioners and policymakers could use both the PI Port Framework and pathways to support them in developing a longer term vision, and formulating strategies and policies.

Chapter 3 is a first stage in the modelling of intelligent agents' performance preferences in evaluating and selecting ports in the PI. Understanding of port users' performance preferences, in terms of port performance indicators with respective weights in the PI, can be used to support port managers in determining their strategy, investment decisions, and management of resources.

By means of an illustrative case, Chapter 4 demonstrates the future capability of PI ports to reposition inbound shipments on the basis of standardized levels of PI containers with appropriate information accessibility and improved visibility in port logistics. It proposes a design of an IT architecture which can be the starting point for developers of information systems in ports. Additionally, it shows that investments in standardization, interoperability of ISs and global T&T systems are key prerequisites for ports to become integral components of a globally functioning PI.

Chapter 5 explores port policy under the uncertain development towards the PI. Here, we analyse various scenarios, taking into consideration the development of technological and institutional aspects. Hereafter, intelligent agents' port performance preferences are analysed with respect to the different scenarios, and potential policy areas are developed. The final result of this chapter is new insights into the effectiveness of the developed policy areas in different scenarios. Understanding which policy areas are effective in particular scenarios provides managers and policymakers with support for making trade-offs between investments and in overall strategy- and policy formulation.

In Chapter 6, we show that the PI, being a relatively young but compelling vision that envisions how many technological and organizational innovations could converge in a real-world FTL system, also addresses many existing cross-industry interests, such as standardization, digitalization, agility, resilience, and environmental sustainability. This chapter focuses on providing port and maritime practitioners with insights into the development of the FTL system towards the PI from a practical perspective, its implications in terms of opportunities and challenges, and the way they could anticipate on and contribute to its realization.

1.5 Thesis outline

The remainder of this thesis follows the subsequent chapters, as introduced in Section 1.3 and Figure 1.2. The individual chapters are identical to the respective journal papers, of which four have been published and one is currently under review. The author of this thesis has led the conceptualization and the execution of the research, as well as the writing of the resulting papers. Table 1.1 shows an overview of the chapters in this thesis with their respective references to the supporting scientific papers and status, at the time of writing.

Table 1.1: *Thesis chapters with respective references*

	Reference
Chapter 2	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*, 102834. **Status: Published**
Chapter 3	Fahim, P.B.M., Rezaei, J., Montreuil, B., & Tavasszy, L. (2021). Port performance evaluation and selection in the Physical Internet. *Transport Policy, In Press.* **Status: Published**
Chapter 4	Fahim, P.B.M., An, R., Rezaei, J., Pang, Y., Montreuil, B., & Tavasszy, L. (2021). An information architecture to enable track-and-trace capability in Physical Internet ports. *Computers in Industry*, *129*, 103443. **Status: Published**
Chapter 5	Fahim, P.B.M., Mientjes, G., Rezaei, J., Van Binsbergen, A., Montreuil, B., & Tavasszy, L. (2022). Alignment of port policy to the context of the Physical Internet. *Under review.* **Status: Under review**
Chapter 6	Fahim, P.B.M., Rezaei, J., Jayaraman, R., Poulin, M., Montreuil, B., & Tavasszy, L. (2021). The Physical Internet & Maritime Ports: Ready for the Future? *IEEE Engineering Management Review*, *49*(4), 136-149. **Status: Published**

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2 On the evolution of maritime ports towards the Physical Internet

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Abstract: 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 within 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 within 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.

2.1 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).

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 (e.g. 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) (Turoff, 1970; Von der Gracht & Darkow, 2010; Gnatzy et al., 2011). A secondary objective of this paper is to derive implications for strategic decision-making of PAs. As ports and their infrastructures are extremely asset heavy with high investment costs and needs (Parola et al., 2013; Notteboom, 2016), 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 in 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 in the PI.

The remainder of the paper is organized as follows. Section 2.2 provides a review of the relevant bodies of literature for our research. In Section 2.3, the methodological approach is outlined. In Section 2.4, the construction of the PI Port Framework (PI PF) and the contextual scenarios are presented and discussed. Section 2.5 presents the results from the Delphi study and the derived PI Port Development Paths (PI PDPs). Section 2.6 presents a discussion that includes the validation, and some managerial implications and recommendations for PAs. Section 2.7 ends the paper by means of a conclusion and recommendations for future research.

2.2 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 et al., 2012a). Conceptual designs of road and railway hubs in the PI were addressed by Ballot et al. (2012b) and Meller et al., (2012), while Crainic & Montreuil (2016) proposed a framework linking concepts of City Logistics to the PI. The layered Open Systems Interconnection (OSI) model, the ISO’s networking model, was analyzed and translated into the PI’s equivalent, the Open Logistics Interconnection (OLI) model (Montreuil et al., 2012a; Colin et al., 2016). The analogy between the DI and the PI was further investigated by Sarraj et al. (2014) and Van Luik et al. (2020). Dong & 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 et al., 2012b). 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. Pan et al., 2015; Krommenacker et al., 2016; Montreuil et al., 2018; Faugère & Montreuil, 2020). Landschützer et al. (2015) and Sternberg & Denizel (2021) studied the modularity aspect of the PI in more detail. Regarding maritime ports, more recently, Fahim et al. (2021a) proposed an information architecture that enables track-and-trace capability in PI ports, whereas Fahim et al. (2021b) 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 significant 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 sea-land gateways with (un)loading activities (first generation ports (GP)) into ports that offer a wider range of logistics and value-added services (3GP) (UNCTAD, 1992), 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 & 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 & 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 & 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. Schuckmann et al., 2012; Liimatainen et al., 2014; 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 in the PI, more specifically. The latter two gaps can be considered methodological, while the first two can be considered as literature gaps.

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 applying scenario development, constructing an evolutionary port development framework, and developing potential pathways for ports towards the PI, we endeavor to provide ports with insights and recommendations to support them in their strategic decision-making.

2.3 Methodology

This section introduces the methodology that is used in this research. As indicated in Figure 2.1, the research process starts with expert interviews for the construction of the 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 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.

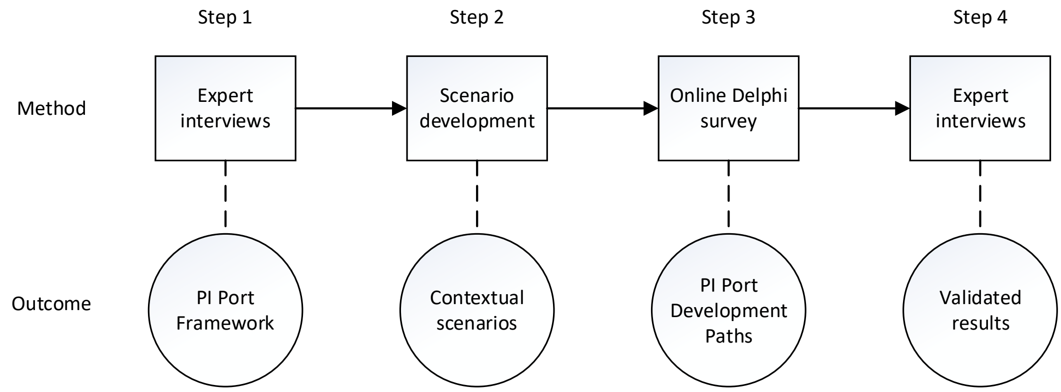


Figure 2.1: *Research process*

2.3.1 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 2.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 2.B.

2.3.2 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. Notteboom, 2016; Tavasszy, 2018; Hahn, 2020) and industry reports (e.g. DHL, 2012; WEF-BCG, 2014; Nowak et al., 2016; Snabe & Weinelt, 2016; Nextnet, 2017; Port of Rotterdam, 2019a; Port of Rotterdam, 2019b), 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 also in line with other transport scenario studies (e.g. Bradfield et al., 2005; Tuominen et al., 2014; Melander, 2018).

2.3.3 Online Delphi survey

As Figure 2.1 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 hence, 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 answers, and yielding an as high as possible response rate and validity of results (Mitchell, 1991). Each round is aimed to be completed in 30 minutes 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. Mitchell, 1991; Hsu & Sandford, 2007; Enserink et al., 2010).

Altogether, 78 qualified experts and potential panelists were identified as having substantial knowledge on port development and/or PI, and 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 of the ALICE-initiative are identified within the European group, of which 20 belonged to industry while the remaining 5 belong to research institutions. We identified and evaluated 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, 2011). 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. Hahn & Rayens, 1999; De Vet et al., 2005). 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 2.C.

2.4 Physical Internet Port Frameweork (PI PF) & Contextual scenarios

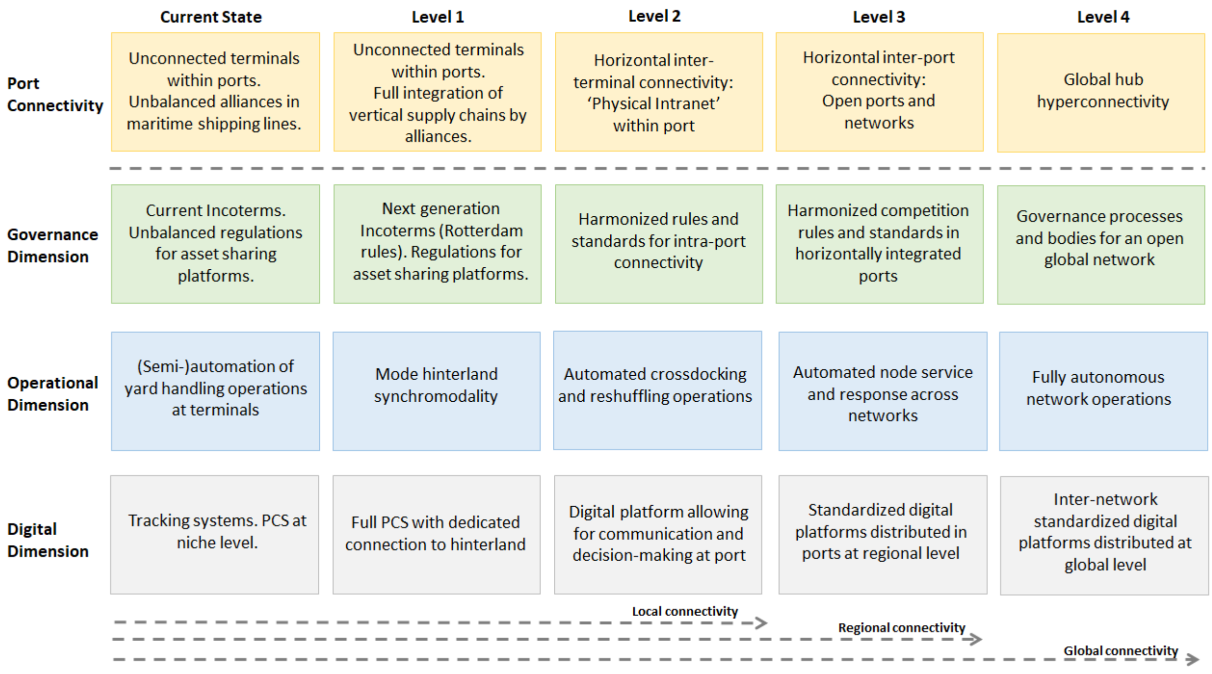
In this section, we consecutively present the PI PF and the contextual scenarios.

2.4.1 Physical Internet 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:

- *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 Figure 2.2, 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.



	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 2.2: *PI Port Framework (PI PF)*

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.

2.4.2 Contextual scenarios

Through a literature review and expert interviews (see Appendix 2.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.

Following the scenario logic approach, as developed by Enserink et al. (2010) and explained in Section 2.3, 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. Taneja et al., 2010; Parola et al., 2017; 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 2.1. 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; Tuominen et al., 2014; Melander, 2018).

Table 2.1: *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

2.5 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*.

2.5.1 Results of the online Delphi survey

Table 2.2 summarizes the most relevant Delphi 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 2.4, 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

Table 2.2: *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**	**ΔSD**
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 SD: Standard Deviation
ART: Average Response Time IQR: Interquartile Range
Median: 0 = Current Situation; 1 = Level 1; 2 = Level 2; 3 = Level 3; 4 = Level 4

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 minutes 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 *governance dimension*, 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.

2.5.2 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. As a first instance, one of the experts suggested 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 shared the idea that ”cross-docking and (re)positioning operations might occur earlier than actual operational synchromodality”. Secondly, the framework was built to use as input for a Delphi, assuming that the three dimensions were independent from each other. Nevertheless, one of the panelists argued that there indeed is a dependency between the three dimensions. Thirdly, although the data element was indeed taken into account by the authors during the development of the PI dimensions, one of the panelists noted that we emphasized too much on the transport and logistics network perspective, while in his opinion the data perspective should have been dominant in the framework. Fourthly, two panelists shared 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”.

2.5.3 PI Port Development Paths (PI PDPs)

Next, the outcomes of the Delphi 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 2.1), the port evolution levels that the three PI dimensions of the PI PF reach in Round 2 of the Delphi, are summarized into Table 2.3, both for the year 2030 and 2040. In addition to the three PI dimensions, the Port connectivity layer has been included in this table. The Port connectivity level, as also explained in Section 2.3, is derived by applying a minimization rule to the three PI dimensions at a specific point in time. The PI PDPs were then created based on the Port connectivity levels, for each contextual scenario, starting at the current state until 2040. This was done for both the mean and the median, and hence, two PI PDPs for each contextual scenario, as also shown in Table 2.3. 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 was visualized using the values of the years 2020, i.e. Current State, 2030, and 2040. The results for all PI PDPs are plotted in Figure 2.3, 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.

Table 2.3: *Summary of evolution levels of the PI Dimensions and the Port connectivity with respect to the mean and median*

		Mean				**Median**			
		Gover-nance	**Operatio-nal**	**Digital**	**Port connectivity**	**Gover-nance**	**Operatio-nal**	**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

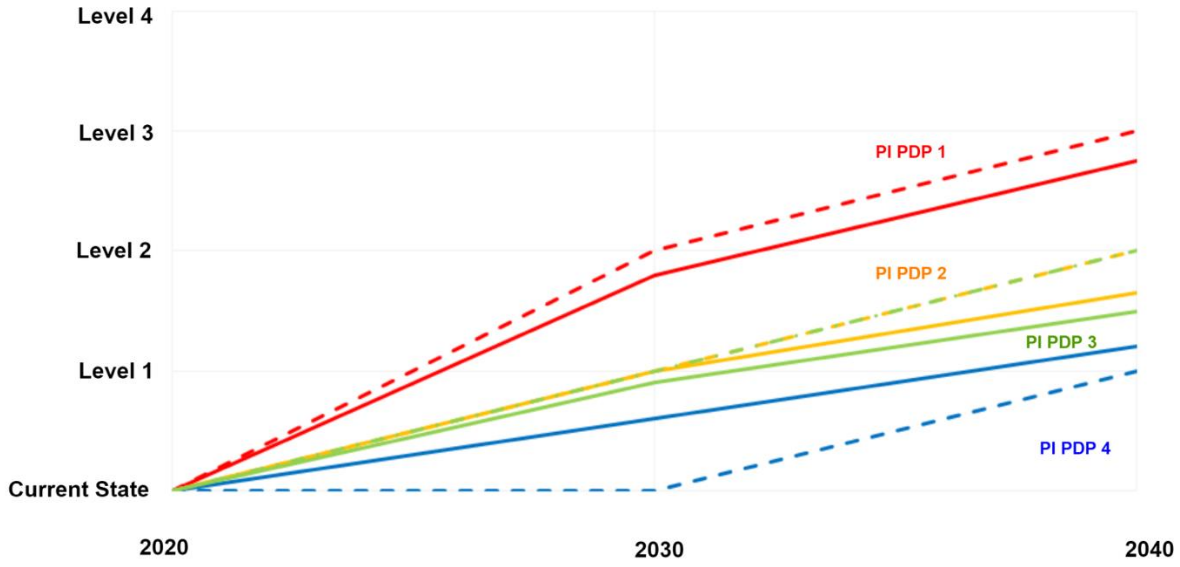


Figure 2.3: *PI Port Development Paths (PI PDPs) – Mean and median in continuous and dashed lines, respectively*

The first contextual scenario was dominated by favorable global institutional integration, where the rise of democracies had expanded to developing countries by 2040. In line herewith, major power blocks, such as USA, China, and the European Union had been 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 resulted 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 Figure 2.2. This means that port terminals (e.g. ECT, DP World, APM Terminals) are horizontally collaborating within the port. Harmonized rules and standards have been 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 terminals have gone 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 Physical Internet.

Both contextual scenarios 2 and 3 had opposing combination of driving forces (see Table 2.1). Scenario 2 was 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 was 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 are 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 involved 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 have steadily continued 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 have also improved their dedicated operations, and ports have implemented Port Management Systems (PMS) 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.

2.6 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 2.3.2.

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. A PA could take the lead in developing a local platform (e.g. PCS) that further connects to regional and global platforms”. Regional and global PCSs 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. As also shown in Figure 2.2, “the coordination and communication (by means of PCSs) 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 by evaluating and monitoring the implementation of new regulations and harmonized rules, such as the upcoming Rotterdam Rules. Keeping stakeholders informed could allow a parallel and joint implementation among countries. Similarly, with the Consortia Block Exemption Regulation (CBER), PAs could either lobby in favor of its extension in 2020, 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 et al., 2021a). Here, investments should be made by both PAs and terminal operators into updating existing and developing new facilities. Mainly, shippers, shipping lines, and LSPs could contribute to the operational dimension by taking a lead in the introduction of standardized modular PI containers.

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.

2.7 Conclusions and future research

The purpose of this paper was to address the literature gap around the future of maritime ports in 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 ”Physical Internet” 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.

Appendix 2.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.*

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 are tabulated in Table 2.A. 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?*

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 2.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 the PI in the context of maritime ports 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 2.B 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. Figure 2.B is a visualization of Table B 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 realistic and plausible?*

Table 2.A: *Contextual factors*

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

Table 2.B: *Summary of evolution levels of the PI dimensions and the Port Connectivity with respect to the mean and median*

		Mean				**Median**			
		Gover-nance	**Operatio-nal**	**Digital**	**Port connectivity**	**Gover-nance**	**Operatio-nal**	**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

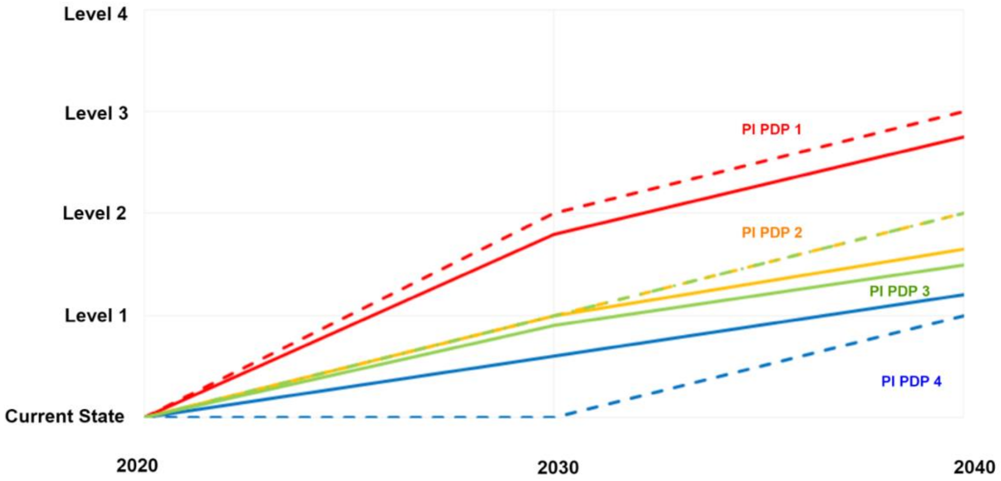


Figure 2.B: *PI Port Development Paths – Mean and median in continuous and dashed lines, respectively.*

Appendix 2.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 2.C). Figure 2.C shows a screenshot of the actual online Delphi survey and gives an impression of how it was conducted.
Round 1 was structured as follows:

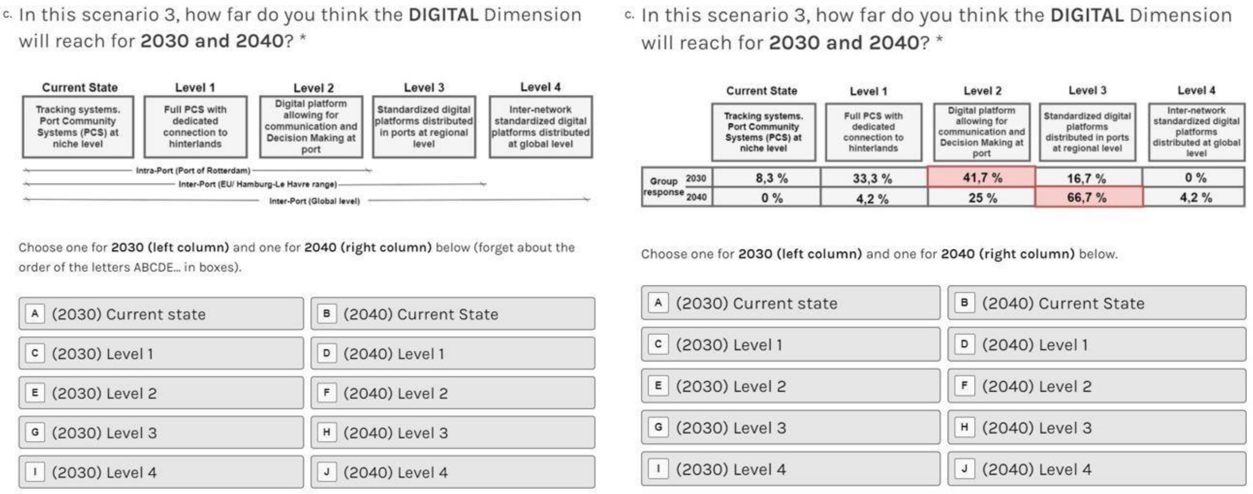
1. A first welcome slide with the reminder that the survey would take between 15 and 25 minutes.
2. An explanation of the purpose of the survey and the PI Port framework was presented.

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.

***Table 2.C:** 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



c. In this scenario 3, how far do you think the **DIGITAL** Dimension will reach for **2030 and 2040**? *

Current State	Level 1	Level 2	Level 3	Level 4
Tracking systems. Port Community Systems (PCS) at niche level	Full PCS with dedicated connection to hinterlands	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

Choose one for **2030 (left column)** and one for **2040 (right column)** below (forget about the order of the letters ABCDE... in boxes).

A (2030) Current state
B (2040) Current State
C (2030) Level 1
D (2040) Level 1
E (2030) Level 2
F (2040) Level 2
G (2030) Level 3
H (2040) Level 3
I (2030) Level 4
J (2040) Level 4

(a)

c. In this scenario 3, how far do you think the **DIGITAL** Dimension will reach for **2030 and 2040**? *

		Current State	Level 1	Level 2	Level 3	Level 4
		Tracking systems. Port Community Systems (PCS) at niche level	Full PCS with dedicated connection to hinterlands	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
Group response	2030	8,3 %	33,3 %	41,7 %	16,7 %	0 %
	2040	0 %	4,2 %	25 %	66,7 %	4,2 %

Choose one for **2030 (left column)** and one for **2040 (right column)** below.

A (2030) Current state
B (2040) Current State
C (2030) Level 1
D (2040) Level 1
E (2030) Level 2
F (2040) Level 2
G (2030) Level 3
H (2040) Level 3
I (2030) Level 4
J (2040) Level 4

(b)

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

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3 Port performance evaluation and selection in the Physical Internet

Fahim, P.B.M., Rezaei, J., Montreuil, B., & Tavasszy, L. (2021). Port performance evaluation and selection in the Physical Internet. Transport Policy, In Press.

Abstract: Maritime ports are an integral part of global trade and the supply network system. An upcoming paradigm for innovation in this system is that of the Physical Internet (PI). This highly advanced way of shipping will present a very different logistics environment with respective challenges for maritime ports. For those investing in or operating port systems, it is important to understand whether different service quality aspects will be important in this future system, compared to today. Our paper deals with the port performance evaluation and selection problem. Although it has been studied extensively in a contemporary context, there has been no exploration of the criteria and preferences of decision-makers in the future shipping environment of the PI. Our objective is to define these criteria and explore their weighting in this new context. We propose two distinct autonomous decision-makers for port performance evaluation and selection in the PI: intelligent containers and vessels. We identify future port performance evaluation and selection criteria, and analyse their weighting based on an expert survey, complementing the extant literature on port performance evaluation and selection, and the PI. We use the Bayesian Best-Worst Method (BWM) to derive weights for the criteria. We find that, compared to the current port performance evaluation and selection literature, in a first stage in the modelling of intelligent agents' performance preferences, subtle differences in weights mark the step from the present towards the PI. Partly, this is reassuring for port authorities as they can manage largely the same set of performance indicators to be attractive for both decision-makers. However, the results also show differences between agents, with an increased importance of, in particular, Level of Service, Network Interconnectivity, and Information Systems.

3.1 Introduction

Maritime ports function as critical facilitators of logistics and international trade, through which they contribute to the economic development of countries and regions (Arvis et al., 2018a). Haraldson et al. (2020) argue that ports should be regarded as dynamic organic systems within both national socio-economic-political and globalized economic systems, in which both economic value creation and complexity have increased over time. Whereas first generation ports merely served as a cargo gateway between land and see, second generation ports started including some warehousing and limited other services. Third generation ports started to become integrated entities in the supply chain with flows of information in addition to the physical flows, while fourth generation ports have started to become connected with other ports in terms of information exchange and setting standards. Current fifth generation ports are often characterised as customer-centric and focused at serving its full community.

An innovation that is expected to impact the current economic and trading patterns, technologies, legislation, and governance systems, is the Physical Internet (PI). The term PI was for the first time introduced in the field of transport and logistics in 2006 on the front page of The Economist (Markillie, 2006). It proposes physical packages to be moved similar to the manner in which data packages move in the digital internet (DI). Later, the PI has been defined as “an open global logistics system founded on physical, digital and operational interconnectivity through encapsulation, interfaces and protocols” (Montreuil et al., 2013: p. 1). The innovation is considered to be a breakthrough in the fields of material handling, logistics, transportation, and facilities design (Pan et al., 2017). It claims to ultimately help achieve economic, environmental, and social efficiency and sustainability (Montreuil et al., 2013). Despite its promises and studies that have shown interesting results (e.g. Sohrabi and Montreuil, 2011; Ballot et al., 2014; Pan et al., 2015; Sarraj et al., 2014; Venkatadri et al., 2016), an all-encompassing innovation of this magnitude also creates new uncertainties for many stakeholders, such as ports, by means of new variables that could impact the future use of the freight transport and logistics system. Intelligent agents as autonomous decision-makers (DMs) is such a new variable that could significantly impact the use of the freight transport and logistics system in a future PI situation. While current port users are often represented by shipping lines, logistics service providers (LSPs), and shippers (Rezaei et al., 2019), we are interested in a similar differentiation in DM perspectives but then in the context of the PI. The PI routing protocol will require a different distribution of decisions over actors, where the envisioned intelligent agents will replace current port users as DMs for port performance evaluation and selection.

As ports’ individual performance heavily influences the competitiveness of entire supply chains, port performance evaluation and selection by its users has become pivotal for competitiveness. Decision-making can be complex and dynamic due to the involvement of various stakeholders and many, sometimes conflicting, criteria. An example of conflicting criteria here would be costs versus service quality, where usually the case is that costs rise when the service quality increases, while often the goal is to keep costs low and service quality high. Insights into how these criteria are weighed can help port users to optimize their supply chain competitiveness. A frequently used approach for analysing port performance and selection in this way is multi-criteria decision-analysis (MCDA). In addition to supporting port users to choose the most suitable port, it can also provide port authorities (PAs) with insight into the preferences of the port users as their potential clients. These insights allow PAs to better understand how to manage their performance and improve their competitiveness, by the appropriate investments and policies.

Since ports and their infrastructures are asset heavy with high investment costs and needs, a thorough understanding, of the manner in which the freight transport and logistics system is developing, is crucial for sustainable (long-term) policymaking. Laird and Venables (2017) argue that policymakers are more and more interested in evaluating transport and logistics performance to understand the effects of, and relationship between, investments and transport and logistics systems performance. The analysis of port performance evaluation and selection has important implications for a port's policy formulation and investment decisions (Martinez Moya and Feo Valero, 2017). Especially in decision-making situations under uncertainty, where investments and long-term policies are being appraised, potential changes in (the valuation of) port performance and selection metrics by its users should be well understood. Hence, although many researchers have investigated port performance evaluation and selection in the current world, the idea of ports inside the PI provides us with an opportunity to position this topic inside an innovative context. This paper, by analysing port performance evaluation and selection from the perspective of intelligent agents in the context of the PI, is a first stage in the modelling of intelligent agents' performance preferences in evaluating and selecting ports.

The main research question to be answered in this paper is as follows: How will port users in the Physical Internet evaluate port performance and select the most suitable port?

By studying maritime port performance evaluation and selection in the PI in this paper, we aim to contribute to:

- the growing stream of PI literature by introducing the aspect of maritime freight, framing port performance evaluation in port selection as a PI network (sub)problem;
- the port performance and port selection literature, through valuation of attributes from the intelligent agents' perspectives; and
- the empirical literature on policy evaluation, by identifying and weighting port performance evaluation and selection criteria for the PI, relevant for future port policies.

The remainder of this paper is structured as follows: Firstly, an overview of the current literature on port selection and the PI will be provided in Section 3.2. Section 3.3 presents the methodology. Section 3.4, firstly, introduces and discusses the conceptual model, and secondly, presents the results and discusses the most relevant interpretations. Section 3.5 contains a discussion and some policy implications. Section 3.6 contains the main conclusions of the research and recommendations for future research.

3.2 Literature review

3.2.1 The Physical Internet and the role of hubs

The PI has claimed to offer a fundamental solution to the current societal, economic, and environmental unsustainability in today's freight transport and logistics systems (e.g. Montreuil et al., 2010; Montreuil, 2011; Montreuil et al., 2013; Ballot et al., 2014), framed by Montreuil et al. (2013) as the Global Logistics Sustainability Grand Challenge. The PI thanks its name to the metaphor of the DI, in which data packets are routed through an interconnected network of nodes (Ambra et al., 2018). Montreuil (2020) used "a hyperconnected global logistics system enabling seamless open asset sharing and flow consolidation through standardized encapsulation, modularization, protocols and interfaces to improve the efficiency and sustainability of serving humanity's demand for physical objects" to define the PI. In addition to a definition, Montreuil (2020) defined the following 8 Building Blocks for the PI: (1) Unified Set of Standard Modular Logistics Containers; (2) Containerized Logistics Equipment and Technology; (3) Standard Logistics Protocols; (4) Certified Open Logistics Facilities and Ways; (5) Global Logistics Monitoring System; (6) Open Logistics Decisional & Transactional Platforms; (7) Smart Data-Driven Analytics; and (8) Certified Open Logistics Service Providers.

Sarraj et al. (2014) advocate that the analogy between the DI and the PI is based on three major characteristics of their networks: (1) the definition of interconnection, (2) the structure of the networks, and (3) the routing of objects through these networks. The idea of the PI is to interconnect all the individual logistics networks through the principles of autonomous systems that are used in the DI (Arjona Aroca and Furio Prunonosa, 2018). Similar to networks in the DI, networks in the PI are envisioned to be structured in hierarchical meshed networks (Montreuil et al., 2018) that allow, firstly, to break the complexity of a network into smaller and more manageable areas, secondly, to accommodate rapid growth by only requiring local modifications, and thirdly, to be able to connect billions of users globally (Medhi and Ramasamy, 2018). Using such a network structure, the PI sustains a fractal interconnection of individual logistics networks (Sarraj et al., 2014). Although many similarities can be found between the DI and the PI, there are also some major differences. Van Luik et al. (2020), therefore, emphasize that the DI/PI analogy should be used for argumentative, illustrative and inspirational purposes, and should only be applied for actual design purposes with reserve.

In line with the PI, and building on the concept of intelligent transport systems, Scholz-Reiter et al. (2006) investigated the possibility of applying DI routing protocols to transport and logistics routing. However, the direct application of DI routing protocols to transport and logistics seems unfeasible due to the differences in time scales of both networks, costs and ease of reproducing packages, and the fact that, in transport and logistics, vehicles are needed to transport packages, which imposes a need for separate package and vehicle routing. To be able to deal with these additional complexities, the distributed logistics routing protocol (DLRP) was developed by Rekersbrink et al. (2009), where dynamic package and vehicle routing are connected and simultaneously applied. In a maritime context of the PI, this could translate into intelligent containers and vessels replacing current port users, i.e. shipping lines, shippers, and LSPs, and making their own decisions autonomously when it comes to selecting ports in their journey through the PI network.

From the perspective of PI hubs, Ballot et al. (2012), Meller et al. (2012) and Montreuil et al. (2012) cover functional designs of a road-rail hub, a road-based transit center, and a road-based crossdocking hub, respectively, in a three-paper series. The objective of the series is to provide designs that are feasible to meet the objectives of these types of facilities, to identify ways to measure the performance of the designs, and to identify research avenues that could further contribute to the design of these facilities. Montreuil et al. (2018) claim that exploiting hyperconnectivity and modularity in the PI provides seven fundamental transformations to parcel logistics hubs: (1) hubs are to receive and ship modular containers encapsulating parcel consolidated by next joint destination; (2) hubs are to exploit pre-consolidation; (3) hubs are to have less direct sources and destinations as the current; (4) hubs are to be ever more multi-actor and multi-modal service providers; (5) hubs are to be more agile through real-time dynamic and responsive shipping times; (6) hubs are to be capable of conducting smart, real-time dynamic decisions on the container consolidation and internal flow orchestration; and (7) hubs are to be active agents in the PI network, dynamically exchanging real-time information on the status of parcels, containers, vehicles, routes, and the other hubs. Although these fundamental transformations are targeted at parcel logistics hubs, the principles should, at least to some degree, also be applicable to maritime hubs. Additionally, an information architecture that enables the track-and-trace capability in PI ports was proposed (Fahim et al., 2021).

For a more extensive review of the PI literature, we refer to Treiblmaier et al. (2020).

3.2.2 Port performance evaluation and selection criteria

To measure a country’s overall logistics performance, since 2007, every two years, the World Bank publishes the Logistics Performance Index (LPI) (Arvis et al., 2018a). The LPI analyses the comparative performance and competitiveness between more than 150 countries with regard to *efficiency of customs*, *quality of trade- and transport-related infrastructure*, *ease of arranging competitively priced shipments*, *competence and quality of logistics services*, *ability to track and trace shipments*, and *timeliness of shipments* as the fundamental elements in logistics (Arvis et al., 2018a). The Global Competitiveness Index (GCI), at a broader level, assesses and monitors the performance of countries on twelve pillars, which is published by the World Economic Forum (WEF), annually (Schwab, 2019). In turn, these twelve pillars can be organized into four indices as presented in Table 3.1.

Table 3.1: *Global Competitiveness Index with respective pillars (adopted from: Schwab, 2019)*

Index	**Pillar**
Enabling Environment	Institutions
	Infrastructure
	ICT adoption
	Macroeconomic stability
Human Capital	Health
	Skills
Markets	Product market
	Labour market
	Financial system
	Market size
Innovation Ecosystem	Business sophistication
	Innovation

Onsel Ekici et al. (2019) and Kabak et al. (2020) studied the relationship between the LPI and the GCI. Onsel Ekici et al. (2019) concluded that governments should focus on ICT adoption, skills, innovation, market size, and infrastructure to facilitate enhanced logistics performance, while Kabak et al. (2020) concluded that national policymakers should primarily invest in business sophistication, financial system, infrastructure, product market, skills, ICT adoption, and innovation to improve the logistics performance of their country. Although the LPI and GCI have become well-known practical tools for policymakers to develop performance enhancing measures, because of its exclusive policy focus and its lacking information basis in terms of industry and business concreteness, they are considered insufficient in coping with decision-making problems that require a deeper capability and institutional analysis (Kinra et al., 2020).

Port performance evaluation and selection is the process of evaluating and selecting the most suitable port by a port user, according to its preferences as part of a transport and value chain (decision), and aims to provide industry and business with concreteness in decision-making problems. The maritime transport chain can be defined as a network of ports and port stakeholders that are involved in the movement of freight over sea. Typically, a port user will have the option to select between alternative ports in a particular geographical region. A port user will select a port according to its preferences, which can often be expressed in port performance evaluation and selection criteria and their respective importance. Table 3.2 provides an overview of current port performance evaluation and selection studies with respective DM perspectives, and criteria. For a more extensive review of the port performance evaluation and selection literature, we refer to Martinez Moya and Feo Valero (2017).

Table 3.2: *Summary of port performance evaluation and selection decision-making perspectives, and criteria*

Author(s)	**Decision-making perspective**	**Criteria**
Bichou and Gray (2004)	Not specified	Financial, throughput, productivity, economic, others
Malchow and Kanafani (2004)	Not specified	Oceanic distance, inland distance, sailing headway, vessel capacity, probability of last port
Tang et al. (2011)	Shipping line	Number of port calls, draught, trade volume, port cargo traffic (TEUs), ship turnaround time, annual operating hours, port charges, availability of intermodal transports
Yuen et al. (2012)	Shipping line, Shipper, LSP	Shipping line: Costs at port, customs and government regulation, hinterland connection, terminal operator, port location, port facility, shipping services, port information system. Shipper: Port location, hinterland connections, port costs, customs and government regulation, shipping services, port information system, port facility, terminal operator LSP: Port location, hinterland connections, shipping services, customs and government regulation, costs at port, port information system, terminal operator, port facility.
Veldman et al. (2013)	Not specified	Inland transport costs, maritime transport costs, other cost and quality of service aspects, choice of coast line, inland transport cargo balance
Kurt et al. (2015)	Shipping line	Location, Connectivity, port operation and performance, port capacity, investment opportunity and decision in the port facility
Magala and Sammons (2015)	Shipping line, Shipper, LSP	Accessibility, connectivity, efficiency, service quality, level of integration, flexibility, port charges, carbon footprint, transit time, frequency, availability, freight rates, reputation, on-time delivery, reliability
Nazemzadeh and Vanelslander (2015)	Shipping line, Shipper, LSP	Port costs, geographical location, quality of hinterland connections, productivity, capacity, costs, quality of operations, reputation of operator, and port location
Van Dyck and Ismael (2015)	Not specific	Port efficiency and performance, political stability, port costs, port infrastructure, cargo volume and port location
Lee and Lam (2016)	Not specified	Reliability, resilient system, ICT, green port development, port cluster, VAS, port connections, inland connections
Arvis et al. (2018b)	Not specified	Container and transshipment volume, port or terminal productivity, roll-on/roll-off volume and services, hinterland connectivity and economic zones, port governance
Chu et al. (2018)	Not specified	Automated equipment, equipment-control systems, terminal control tower, human-machine interactions, interactions with the port community
Ha et al. (2019)	Not specified	Productivity, lead time, human capital, organisation capital, service reliability, service costs, intermodal transport systems, VAS, IC systems, IC integration practices

Port of Rotterdam (2019)	Not specified	VAS, port-related employment, decarbonisation, public-private investments, connectivity, safety, air quality, global hub function
Rezaei et al. (2019)	Shipping line, Shipper, LSP	Total costs, maritime transit time, inland transit time, frequency of shipping, satisfaction deep sea, first port of call, customs service, frequency inland lines, last port of call, satisfaction terminals, number of inland operators, port reputation, number of terminals
Dong and Franklin (2021)	Shipper	Cost, time, schedule, emissions, capacity

As can be observed from Table 3.2, factors related to costs, connectivity, location, capacity, reliability, efficiency, transit time, and IT have been most frequently used in port performance evaluation and selection literature, which also show similarities with the LPI. Additionally, various studies show that the different DM perspectives may have divergent preferences (e.g. Yuen et al., 2012; Magala and Sammons, 2015; Nazemzadeh and Vanelslander, 2015; Martinez Moya and Feo Valero, 2017; Rezaei et al., 2019). Consequently, Martinez Moya and Feo Valero (2017) distinguish between Landside parties, i.e. shippers and LSPs, and Seaside parties, i.e. shipping lines, which function as port selection DMs. While shipping lines tend to design their service networks in such a way that they can gain as much as possible from economies of scale and maximize profits (Guy and Urli, 2006), shippers aim to minimize costs (Talley and Ng, 2013), whereas LSPs' main objectives are to maximize profits by means of consolidation while simultaneously providing their clients with optimal value added services (VAS) (Magala and Sammons, 2015). We are interested in a similar differentiation in DM perspectives but then in the context of the PI, where the PI routing protocol will require a different distribution of decisions over actors, i.e. where intelligent PI containers and vessels will replace the current port users as DMs for port selection.

3.2.3 Future ports

When considering future ports, Song and Cui (2014) stress to distinguish between technological progress, which is the consequence of innovation or (adoption of) new technology, and technical efficiency, which is driven by managerial capacity to maximize outputs, given input levels. Lee and Lam (2016) claim that ports are increasingly being confronted with complex issues arising from recent developments, such as, big data, clustering, and social and environmental concern. As major differences with previous and current generations of ports, they identified an increasing importance for reliable port services, sharing capability of (cargo) information flows among port stakeholders, high-end technology driven and IT solutions, sustainability, physical and digital port connectivity, and VAS. Chu et al. (2018) argue that, due to the structured, predictable, repetitive, and straightforward nature of port operations, the cornerstones of future ports will be automation and technology, which have the potential of transforming ports into highly flexible and reliable logistics hubs with the support of the use of (big) data and advanced analytics. In addition, they stress the importance of digital solutions and real-time connectivity among key supply chain entities and stakeholders, which could improve many variables in networks throughout entire value chains. Ha et al. (2017; 2019) concluded that service reliability, connectivity (with intermodal freight transport systems), VAS, advanced ICT systems, and integration practices are gaining importance in port systems. Port of Rotterdam (2019) recently published a policy document, stating that, going forward, it will focus on developing its global hub function, industrial cluster, connections between the port, city and region, land and infrastructure, human capital, and innovation ecosystem.

3.2.4 Literature gaps and expectations

Although some preliminary design exercises have been conducted on different hub facilities and network (routing) protocols in the PI, no study yet has been conducted that focuses on the investigation of maritime ports in general, and maritime port performance evaluation and selection more specifically.

To be able to perform at the expected level, and support the envisioned hyperconnectivity, modularity, and network structure of the PI, Montreuil et al. (2018) proposed seven transformations for logistics hubs. In line with other works, they increasingly emphasize the need for advanced automation and smart ICT solutions in ports to become more active agents in supply chains, and facilitate and support its community's requirements regarding real-time data processing and sharing, physical and digital connectivity, and overall responsiveness to (changes in) the network.

Furthermore, we expect that the manner in which port performance evaluation and selection will be conducted in the PI will be different than the traditional way of evaluating and selecting ports. In the PI, not only will the DMs be different, by intelligent containers and vessels routing themselves through the logistics network, but also port performance evaluation and selection will be expected to be made at an operational level in a dynamic context and based on real-time information, rather than at a tactical level in a static context.

The currently ongoing and expected future developments in the freight transport and logistics system further complicate the major challenges for the capital-intensive maritime port industry to cope with conflicting interests and uncertainties in attributing operational and investment decisions. Reflecting on the GCI and LPI, we expect that policymakers should focus even more on ICT adoption and innovation in managing their ports, which should increasingly contribute to an overall higher LPI in the PI. However, by means of analysing port performance evaluation and selection criteria with their respective importance from the perspective of intelligent containers and vessels, i.e. the demand side, in the PI, we aim to gain concrete insights into the manner in which conflicting interests and uncertainties in operational and investment decisions for ports can be addressed.

3.3 Methodology

The most frequently applied methods to approach port performance evaluation and selection are MCDA and discrete choice modelling. The advantage of using MCDA is that actual choice situations do not have to be specified. We will therefore rely on MCDA methods positioned within the PI context to evaluate the importance of port performance and selection criteria. Amongst several MCDA methods, BWM allows us to obtain the weights of criteria with the need of less data than alternative methods (e.g. AHP), while simultaneously leading to more consistent and reliable results (Rezaei, 2015). By initially selecting the best and worst criteria, after which all other criteria are compared with these two, the method is well structured, easily executable, and time-efficient. The structure also helps the DM to gain additional valuable insights from the pairwise comparisons. Furthermore, the use of only integers can prevent a fundamental distance problem that could occur with the use of fractions in the pairwise comparisons (Rezaei, 2015), while the use of two opposite references (best and worst) mitigates the anchoring bias of a respondent (Rezaei, 2020). For related recent applications of BWM on topics such as the LPI, port performance, spatial distribution structures, and crowdsourcing delivery, we refer to Rezaei et al. (2018), Rezaei et al. (2019), Onstein et al. (2020), and Li et al. (2020), respectively.

Our empirical research approach is built around the MCDA method and is as follows (see Figure 3.1):

- Step 1 aims to establish the set of criteria. For this purpose, we conduct a series of 10 semi-structured face-to-face expert interviews. We use the semi-structured format to be able to give the experts some direction, while also allowing them to express their opinions and add to the discussion. We selected the 10 experts based on their experience with ports and/or PI, from academia, applied research institutes, and industry. Appendix 3.A provides a list of the experts with respective functions and affiliations.
- In step 2, a survey among a group of experts is conducted to obtain data as input for the Bayesian BWM. The group comprised 34 experts from academia, applied research institutes, and industry. These experts are selected based on their academic experience with ports and/or PI, their (scientific) contributions to ports and/or PI, and industry experience. Appendix 3.B presents the list of the experts that participated in the survey.
- In Step 3, since we are dealing with the preferences of a group of experts, we employ the Bayesian BWM. The Bayesian BWM is a pairwise comparison-based MCDA and is specifically designed to obtain the relative priorities, i.e. aggregated final weights, of criteria for a group of DMs all at once (Mohammadi and Rezaei, 2020a). In addition to obtaining the relative priorities, another valuable feature of the Bayesian BWM is that it provides ranking schemes, called credal rankings, which are able to measure the degree to which a group of DMs prefer one criterion over another by means of a confidence level (Mohammadi and Rezaei, 2020b). The group shows to be more certain about the relationship between two criteria if the respective confidence level is high. The comparisons of the criteria with their respective confidence levels are visualized using weighted directed graphs.

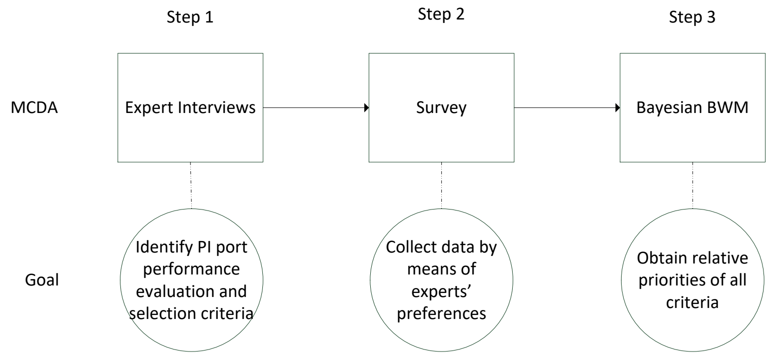

Figure 3.1: *Research methodology*

3.4 PI port performance evaluation and selection

3.4.1 Criteria

Table 3.3 tabulates the set of criteria that have been established by means of executing Step 1 of the Methodology. In order to select the most suitable port, each decision alternative, i.e. port, should be evaluated against the set of criteria. The criteria are grouped into four classes (see Table 3.4). Transport Chain Quality (TCQ) considers criteria that are not restricted to the port itself, but consider the complete transport chain instead. The Costs class considers the criteria that are directly related to the costs of the transport chain and the costs incurred at the port, while Technology considers criteria at the port that are technology driven. Network Quality of Port (NQP) considers the criteria that contribute to the quality of the port in the network. Most of the criteria are directly linked to the PI literature and can be categorized into one of the eight PI Building Blocks.

Table 3.3: *Port performance evaluation and selection criteria with respective descriptions*

Criterion	**Description**
A1. Level of Service (LoS)	Factors describing *level of service (LoS)* quality such as transit time (Sarraj et al., 2014; Rezaei et al., 2019), availability of vessel (Ballot et al., 2012), port throughput time (Meller et al., 2012), port and route congestion (Montreuil et al., 2012b), and agility, flexibility and responsiveness (Montreuil et al., 2018). These factors are becoming increasingly more important in today's logistics, and are expected to keep doing so in the dynamic environment of the PI, where agility, flexibility, and responsiveness are essential elements of the network (Montreuil et al., 2018).
A2. Reliability	The *reliability* of the transport chain is reflected by the potential risk of complete port and/or vessel disruption, the defect and loss rate, financial stability of port and/or vessel (company) (Rezaei et al., 2014), and the client rating of a particular route with respective ports (Ballot et al., 2014), based on historical and real-time data, and future predictions. Client rating is based on a system that will allow users to assess service providers by means of a PI rating (Ballot et al., 2014).
A3. Physical Port Infrastructure (PPI)	*Physical port infrastructure (PPI)* includes the factors number of terminals (Ballot et al., 2012), available handling capacity (Nazemzadeh and Vanelslander, 2015), and overall efficiency of the PPI (Martinez Moya and Feo Valero, 2017). Whereas LoS reflects the actual state of the operations, the first two factors here are related to the potential overall capacity of the PPI, while the overall efficiency is related to the potential pace in which a container and vessel can move through, i.e. in and out of, a port.
A4. Sustainability	Strengthening the environmental *sustainability* of the global freight transport and logistics system is ultimately one of the goals of the PI (Montreuil et al., 2012a). Here, we include port emissions, vessel emissions, nuisances (to the port environment) (Ülengin et al., 2010; Sarraj et al., 2014), social responsibility (Rezaei et al., 2014), and air quality and noise (Caramuta et al., 2018).
A5. Safety & Security (S&S)	*Safety* concerns labour related injuries and casualties caused by both vessel transport and container handling operations at the port (Caramuta et al., 2018). *Security* addresses the traditional issue of theft (Kheybari and Rezaie, 2020) and the increasingly important issue of cybersecurity. The latter is to play a crucial role in the digitally hyperconnected system of the PI.
B. Costs	*Transportation costs* will be dependent on a particular vessel with respective route (Sarraj et al., 2014; Rezaei et al., 2019), while the *transshipment costs (TC)* are variable and relate to the handling and operations charges at a specific port or terminal from a container perspective. *Seaport duties (SD)* are fixed costs and directly paid by vessels(' companies) to ports to be able to call at a port and retain their services (Yuen et al., 2012). Here, it must be kept in mind that a vessel will only call at a particular port when a minimal critical number of containers will be (off)loaded at that port. In the PI, this will be done dynamically and during the voyage before reaching a port.

C1. Automation of Operations (AoO)	*Automation* here represents a port's equipment and technology to conduct operations that are critical for the PI, such as (off)loading, handling and reshuffling of PI containers in an automated manner (Montreuil et al., 2015). The capability of handling a Unified Set of Standard Modular PI Containers will be a prerequisite for a port to be able to operate and participate in a fully operational PI network (Montreuil, 2019).
C2. Information Systems (IS)	*Information Systems (IS)* refers to the level of sophistication of ISs, such as Port Community Systems (PCS) to which all port actors are connected (Chu et al., 2018), but also (internal) track-and-tracing systems. Well-functioning PCSs will be able to serve the more multi-party and multi-service nature of PI hubs (Montreuil et al., 2018). Also, seamless integration and interoperability of IS (Ha et al., 2019)), data availability and accessibility, data transparency, data accuracy and quality, and real-time availability of data are included here.
C3. Smart	Becoming an open data-centric smart global network is one of the foundations of the PI. *Smart* represents the manner and degree to which ports and vessels use optimization, heuristics, simulation and machine learning techniques to optimize their communicational and decisional capabilities (Montreuil, 2019). In addition, one of the suggested fundamental transformations for PI hub design is hubs' capabilities to conduct smart dynamic decisions on the container routing and the internal flow orchestration (Montreuil et al., 2018).
D1. Geographical Location (GL)	The *geographical location* of a port is of importance (Kinra, 2015; Nazemzadeh and Vanelslander, 2015). Here, we consider both the inland distance (from origin to port and/or port to inland destination) and the oceanic distance (from port to port) of the route (Magala and Sammons, 2015). In addition, we refer to a port's natural (dis)advantages regarding its location, such as a port's accessibility by (deep-sea) navigable waterways (Rodrigue, 2016), and its draft restrictions (Castelein et al., 2019).
D2. Logistics (LF)/Maintenance Facilities (MF) around Ports	*Logistics facilities (LF)* around ports, such as warehousing, VAS (Lee and Lam, 2016), and customs procedures (Kinra, 2015) are relevant from a container perspective. *Maintenance facilities (MF)* around ports for vessels for repair purposes also contribute to the network quality of ports. PI hubs are to become more multi-party and multi-service (Montreuil et al., 2018).
D3. Network Interconnectivity (NI)	By means of the *network interconnectivity (NI)*, we refer to a port's both maritime and hinterland connectivity (Lee and Lam, 2016), a port's intermodal connections (Tongzon, 2009; Kinra, 2015; Ha et al., 2019), and frequency of shipping at a port (Ballot et al., 2012). Port connectivity represents the number of both foreland and hinterland nodes that a port is connected to (Magala and Sammons, 2015).

3.4.2 Criteria weights

After having obtained all experts' preferences by means of a survey (Step 2 of the Methodology), we applied the Bayesian BWM to compute the aggregated weights of the criteria as well as the respective credal rankings (Step 3 of the Methodology). In this section, we present and discuss the class and criteria priorities with some notable credal rankings. The credal rankings are presented in a weighted directed graph, where the nodes represent the priorities and each link $s \overset{v}{\Rightarrow} s'$ indicates that criterion s is more important than criterion s' with confidence v. At first, we present the results from the container and vessel perspective individually, after which we provide a comparison between the two.

The container perspective

Table 3.4 presents the classes and criteria with the respective means of the weight distributions in terms of local and global weights. Local weights indicate the weights within the respective class, while global weights indicate the overall weights. It can be directly observed from the table that Costs (0.325) are perceived as the most important class, followed by TCQ (0.305), NQP (0.225), and Technology (0.145). On a criteria level, we can observe that Transport Costs (0.205), Transshipment Costs (0.120), LoS (0.092), NI (0.091), and GL (0.077) are considered most important.

Table 3.4: *Weights of classes and criteria from a container perspective*

Container				
Class	**Global Weight**	**Criterion**	**Local Weight**	**Global Weight**
Class A: Transport Chain Quality (TCQ)	0.305	A1. Level of Service (LoS)	0.300	0.092
		A2. Physical Port Infrastructure (PPI)	0.154	0.047
		A3. Reliability	0.239	0.073
		A4. Safety & Security (S&S)	0.201	0.061
		A5. Sustainability	0.106	0.032
Class B: Costs	0.325	B1. Transport Costs	0.630	0.205
		B2. Transshipment Costs (TC)	0.370	0.120
Class C: Technology	0.145	C1. Automation of Operations (AoO)	0.281	0.041
		C2. Information Systems (IS)	0.445	0.065
		C3. Smart	0.274	0.040
Class D: Network Quality of Port (NQP)	0.225	D1. Geographical Location (GL)	0.342	0.077
		D2. Logistics Facilities (LF)	0.253	0.057
		D3. Network Interconnectivity (NI)	0.405	0.091

Based on Figure 3.2, which shows the credal ranking of the classes from a container perspective, we can conclude that Costs (0.325) is considered the most important class with a full confidence of 1 over NQP (0.225) and Technology (0.145). However, Costs is superior over TCQ (0.305) with merely a confidence level of 0.70, simultaneously indicating that TCQ is superior over Costs with a confidence level of 0.30. Although it has been argued that a confidence level of 0.50 can be used as a threshold value (Mohammadi and Rezaei, 2020a), it does indicate that there is some dissension between the experts' opinions about this particular relationship.

Figure 3.3 shows the credal ranking with respective confidence levels of the criteria within the Technology class. It can be observed that ISs (0.065) are considered more important than both AoO (0.041) and Smart (0.040) systems with a full confidence level. However, AoO is considered more important than Smart with a confidence level of 0.57, implying that these criteria are considered almost equally important among the different experts. All other credal rankings of the criteria from a container perspective have shown to be in full or almost full confidence levels. Hence, the conclusion can be drawn that all other class and criteria weights, shown in Table 3.4, are determined with full or almost full confidence levels.

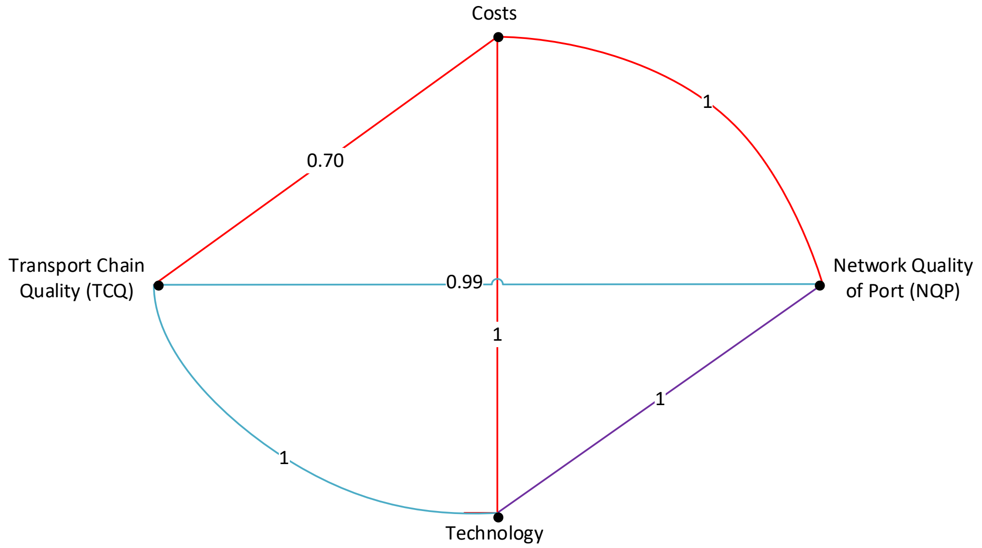

Figure 3.2: *The credal ranking of classes from a container perspective*

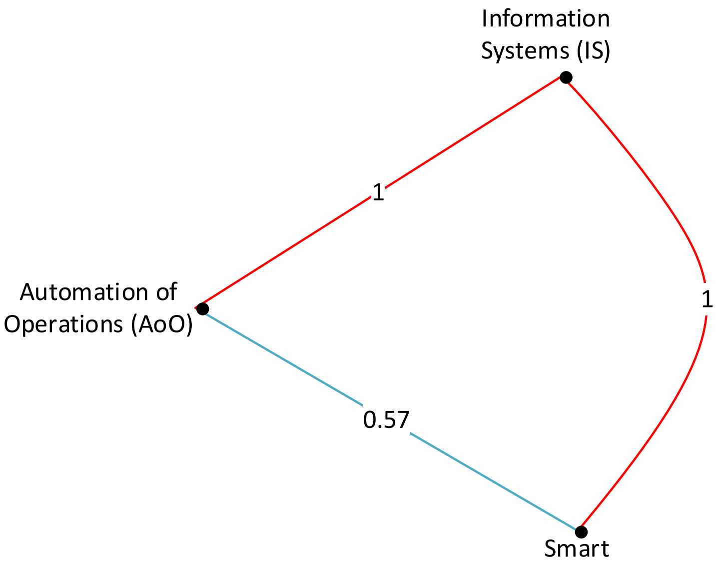

Figure 3.3: *The credal ranking of Technology criteria from a container perspective*

The vessel perspective

Table 3.5 presents the classes and criteria with the respective means of the weight distributions in terms of local and global weights. It can be directly observed from the table that also here Costs (0.369) are perceived as the most important class, followed by TCQ (0.264), NQP (0.207) and Technology (0.160). On a criteria level, we can observe that Transport Costs (0.213), SD (0.156), GL (0.091), LoS (0.076), and ISs (0.072) are considered most important. Figure 3.4 shows the credal ranking with respective confidence levels of the criteria within the TCQ class. All the confidence levels show to be full or almost full, except from Reliability to PPI with 0.72, which means that there is some more dissension between the experts' opinions about this particular relationship than between others. All other credal rankings of the classes and criteria from a vessel perspective have shown to be in full or almost full confidence levels. Hence, the conclusion can be drawn that all other criteria weights, shown in Table 3.5, are determined with full or almost full confidence levels.

Table 3.5: *Weights of classes and criteria from a vessel perspective*

Vessel				
Class	**Global Weight**	**Criterion**	**Local Weight**	**Global Weight**
Class A: Transport Chain Quality (TCQ)	0.264	A1. Level of Service (LoS)	0.287	0.076
		A2. Physical Port Infrastructure (PPI)	0.216	0.057
		A3. Reliability	0.229	0.060
		A4. Safety & Security (S&S)	0.173	0.046
		A5. Sustainability	0.095	0.025
Class B: Costs	0.369	B1. Transport Costs	0.578	0.213
		B2. Seaport Duties (SD)	0.422	0.156
Class C: Technology	0.160	C1. Automation of Operations (AoO)	0.302	0.048
		C2. Information Systems (IS)	0.447	0.072
		C3. Smart	0.251	0.040
Class D: Network Quality of Port (NQP)	0.207	D1. Geographical Location (GL)	0.439	0.091
		D2. Maintenance Facilities (MF)	0.245	0.051
		D3. Network Interconnectivity (NI)	0.316	0.065

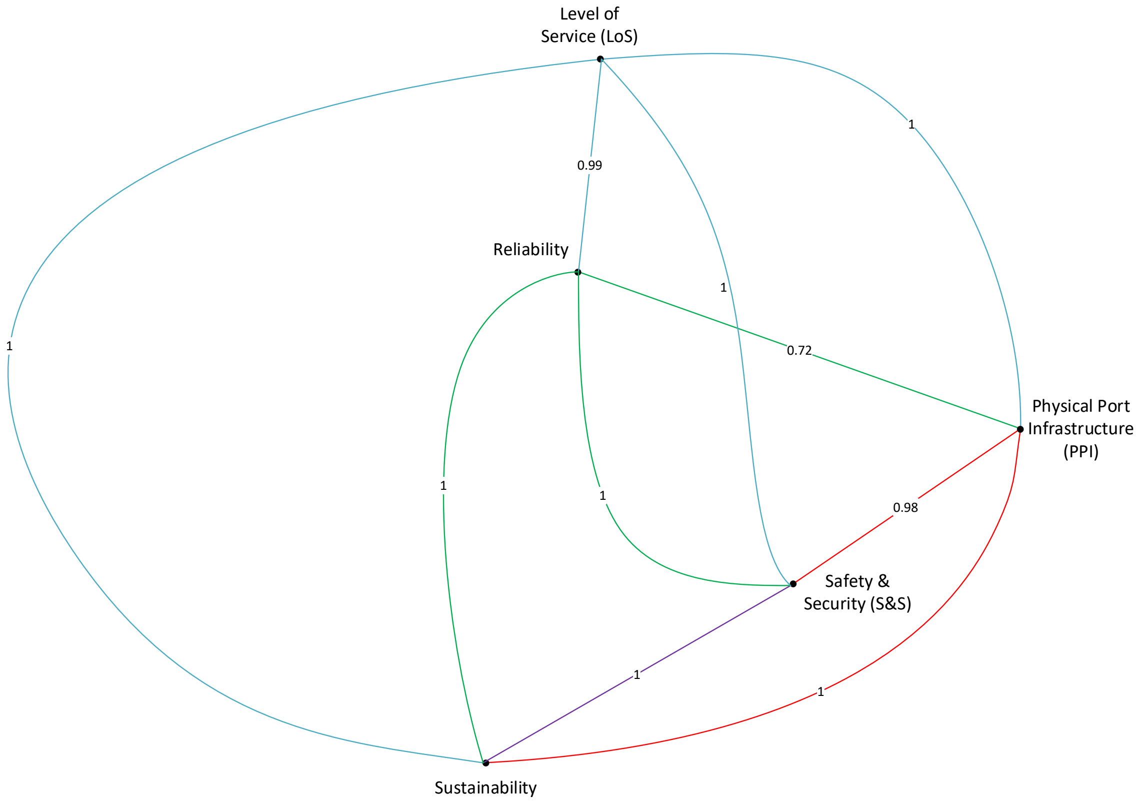

Figure 3.4: *The credal ranking of TCQ criteria from a vessel perspective*

Comparison

Figure 3.5 shows the results from both a container and vessel perspective on class level. At first sight, the results from both perspectives look similar. In both cases, Costs are the most important class, followed by TCQ, NQP and Technology, in that order. The strongest discrepancies between the container and vessel perspective can be found in Costs and TCQ. Costs show to be more dominant from the vessel perspective, while TCQ is considered more important from a container perspective. Weaker relative discrepancies are found in Technology and NQP. Vessels have been found to value Technology more, while containers have a higher preference for NQP.

	TCQ	Costs	Technology	NQP
🟦 Container	0,305	0,325	0,145	0,225
🟥 Vessel	0,264	0,369	0,160	0,207

Figure 3.5: *Classes' global weights comparison between container and vessel perspective*

Figure 3.6 and Table 3.6 show the results from both a container and vessel perspective on a criteria level. At first sight, again, the results from both perspectives look similar. However, the strongest discrepancy can be found in the importance that vessels attribute to SD and containers attribute to TC. Vessels consider SD as more important than containers consider TC. Although these are different criteria, they both measure the costs incurred by means of going to or through a port. Hence, here we could argue that less ports on a particular route is more important to a vessel than to a container. The second strongest discrepancy can be found in NI. This criterion is considered more important from a container perspective than from a vessel perspective. Here, we can argue that experts value the importance of a container having ample intermodal connections and connecting ports in reach to route to their final destination higher than similar traits for vessels, including the importance of consolidation opportunities for a vessel. The third strongest discrepancy can be found in S&S and LoS. S&S is considered more important from a container perspective than from a vessel perspective. Here, it can be argued that it seems plausible that cargo owners are more concerned over the wellbeing of their cargo than the vessels are concerned over the cargo and general safety. Although LoS is also significantly important to the vessel, the higher importance from a container perspective can be explained by the pressure that nowadays rests on suppliers and end-to-end service providers to make sure that their cargo arrives at their customer rapidly and on time. The lowest discrepancies have been found in Smart, LF/MF, Sustainability, and IS.

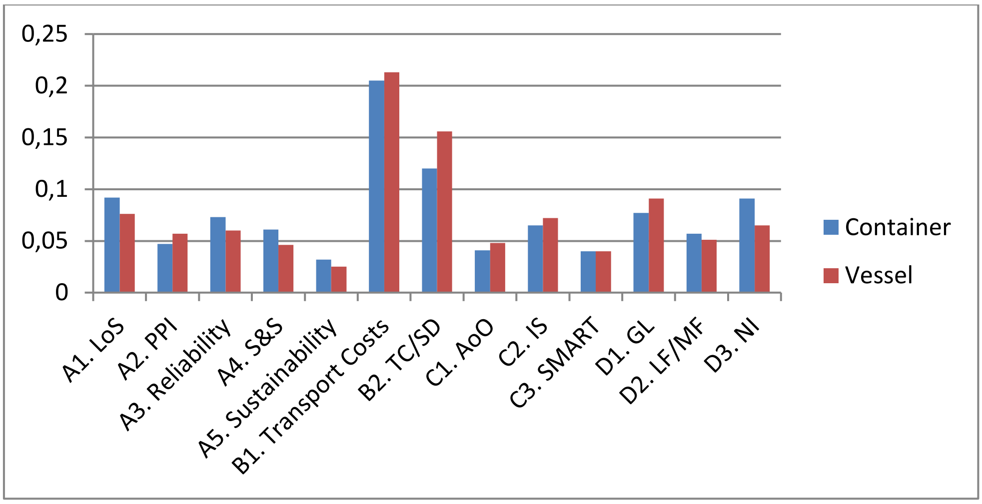

Figure 3.6: *Criteria's global weights comparison between container and vessel perspective*

Table 3.6: *Criteria's global weights comparison between container and vessel perspective*

Criterion	**Global Weight (Container)**	**Global Weight (Vessel)**
A1. Level of Service (LoS)	0.092	0.076
A2. Physical Port Infrastructure (PPI)	0.047	0.057
A3. Reliability	0.073	0.060
A4. Safety & Security (S&S)	0.061	0.046
A5. Sustainability	0.032	0.025
B1. Transport Costs	0.205	0.213
B2. Transshipment Costs (TC)/Seaport Duties (SD)	0.120	0.156
C1. Automation of Operations (AoO)	0.041	0.048
C2. Information Systems (IS)	0.065	0.072
C3. Smart	0.040	0.040
D1. Geographical Location (GL)	0.077	0.091
D2. Logistics (LF)/Maintenance Facilities (MF)	0.057	0.051
D3. Network Interconnectivity (NI)	0.091	0.065

3.5 Discussion

Information on the above criteria is of crucial importance to support PAs in their consideration of investment directions and the design of policies to enhance the competitiveness of their ports (Martinez Moya and Feo Valero, 2017; Van der Lugt et al., 2017). In this section, we position our findings in the literature, reflect on the expectations stated in Section 3.2, and discuss some policy implications for PAs.

Table 3.7 tabulates the most important criteria from both a container and vessel perspective that we found in our research. We can see that the 6 most important criteria, although in a different order of importance, are the same from both perspectives.

Earlier work that considered the three traditional port evaluation and selection perspectives (shipping line, shipper and LSP) by Yuen et al. (2012), Nazemzadeh and Vanelslander (2015), Martinez Moya and Feo Valero (2017), and Rezaei et al. (2019) considered factors related to costs, connectivity, location, and level of service, such as productivity, efficiency, effectiveness, and transit time, as most important. These earlier findings seem to be in line with the results of our own research. However, a difference can be observed in the presence and importance of IS, NI, and LoS from both a container and vessel perspective.

Table 3.7: *Most important criteria from a container and vessel perspective*

Rank	**Container**	**Vessel**
1	Costs	Costs
2	Level of Service (LoS)	Geographical Location (GL)
3	Network Interconnectivity (NI)	Level of Service (LoS)
4	Geographical Location (GL)	Information Systems (IS)
5	Reliability	Network Interconnectivity (NI)
6	Information Systems (IS)	Reliability

Overall, the relatively low weights of criteria, such as Sustainability, Smart, AoO, and PPI can perhaps be considered somewhat unexpected since the PI has been described as a system with its core foundations including automation technology and optimized operations to eventually be able to provide a solution to the current environmental unsustainability in freight logistics. However, at the same time, criteria NI, ISs and LoS have been perceived as highly important criteria, which is in line with the principles of the PI and our earlier stated expectations in Section 3.2. The high importance of NI is in line with the expectation that both containers and vessels are more likely to select a port where the opportunity is greater to catch a vessel that follows a desirable route, and where the opportunity is greater to (un)load a larger number of containers, respectively. The high importance of IS is fully in line with our stated expectation that ports in the PI are required to becoming more active agents in (digital) supply chains, and facilitate and support its community's needs regarding real-time data processing and sharing, and physical and digital hyperconnectivity. The high importance of LoS is, again, fully in line with earlier stated expectations that PI hubs will require to become more efficient, agile, and responsive through real-time dynamic decision making on the container consolidation and internal flow orchestration. Another clear observation is that Costs are perceived as by far the most important criterion, which is in line with the current port selection literature and cannot be considered surprising taking into account the nature of the logistics function and business environment in general.

Reflecting on GCI and LPI, from our results, we can draw similar conclusions as ¨Onsel Ekici et al. (2019) and Kabak et al. (2020). We argue that policymakers, from a port management perspective towards a future PI situation, should focus even more on ICT adoption and innovation, to further increase efficiency of customs, ease of arranging competitively priced shipments, competence and quality of logistics services, and the ability to track and trace shipments, while taking into account commercial pricing strategies in the markets. Simultaneously, PAs could invest in optimizing operations, and improving infrastructure and overall connectivity to ensure quality of trade- and transport-related infrastructure, and timeliness of shipments. Regarding human capital, there is a bit of a paradox since one might argue that, one the one hand, blue-collar labour might become obsolete and unnecessary because of automation and intelligence within systems, while simultaneously more complex systems ask for increasingly skilled, competent, and educated labour.

Overall, the aligned (importance in) port performance evaluation and selection criteria from both the container and vessel perspective makes it easier in terms of trade-offs for policymaking. Hence, these are the areas of investments a port should also make in the PI, according to our results.

When implementing port performance measures, however, it must be kept in mind that ports are still very dissimilar (Bichou and Gray, 2004). Hence, although we provide general policy directions that are applicable to ports in general, more detailed and specific measures could follow from specific case studies. Additionally, the specific hierarchical meshed PI network structure has not been taken into account in our research. According to Montreuil et al. (2018), overall, the hierarchy in PI networks should result in increased consolidation and enhanced operations inside the hubs. Still, the expectation is that different layers in the PI network require hubs that correspondingly fulfil the particular needs of that layer. Furthermore, the notion of certified facilities in the PI might suggest the adoption of minimum evaluation scores on (some) criteria, which could be addressed in future research. Another limitation of our study is that we have collected data from experts and analysed them without further dialogue. We think that communicating the findings with the experts and asking for their updated opinion could lead to an even higher level of accuracy and consensus.

3.6 Conclusions and future research

The main research question that was formulated in the beginning of this paper is: *How will port users in the Physical Internet evaluate port performance and select the most suitable port?* We find a gap in the literature that identifies port performance evaluation and selection from the perspectives of intelligent containers and vessels, in the context relevant for the PI, i.e. one of dynamic routing of shipments and vehicles in a global network. With this paper, we aim to contribute to (1) the growing stream of PI literature by introducing maritime freight, framing port performance evaluation and selection as a PI network (sub)problem, (2) the port performance evaluation and selection literature, through valuation of attributes from the intelligent container and vessel perspectives, and (3) both identifying and weighting port performance evaluation and selection criteria for the PI, with implications for future port policies.

Our main findings include the following. There are subtle differences between the container and vessel perspectives. Although, at the highest level, the ranking of the criteria is the same from both perspectives, there are significant differences in the importance of the underlying criteria. In particular, (1) Transport Chain Quality is relatively more important for containers and Costs for vessels, (2) Level of Service, Network Interconnectivity, and Information Systems appear to be more important for port performance evaluation and selection in general than identified in earlier works, and (3) the weighting of Costs differs per cost type (mostly Transshipment Costs for containers and Seaport Duties for vessels).

For port authorities, the generally good alignment of criteria and their weights between containers and vessels is reassuring, as they can largely manage one set of criteria to remain attractive for both. Also, some subtle differences have been made transparent in this research, which allows them to be managed separately. Apart from attention to different cost aspects for containers and vessels, more emphasis is needed on investments to become more agile, responsive and flexible, as well as on information systems, i.e. digital connectivity and visibility, to be able to support real-time dynamic decision-making capabilities, and enhanced cooperation between actors and supply chains in the PI. In addition, to be competitive in the PI, port authorities should continuously improve their maritime and multi-modal hinterland connectivity.

As avenues for future research, we would like to recommend a regular re-evaluation of the (importance of the) criteria. As the PI can be considered to still be a young concept, the changes it will bring in the freight transportation and logistics system will become more evident over time. This will bring more clarity to experts in the field as to which new port evaluation criteria might arise and the assessments of respective importance. In that sense, this study serves as a basis for future studies as the PI comes closer to realization. Future research could also address the use of minimum threshold values, in terms of minimum scores of ports on evaluation criteria, as to become PI certified and allowed to participate in the PI network. Although we have touched upon the potential policies for ports to become competitive in the PI, more concrete policy measures for both shorter and longer term could be studied. This could be done in various ways, of which one would be by means of modelling maritime freight flows, while integrating the BWM model developed in this paper. The notion of a hierarchical network (local, regional, global) could also be integrated here. Furthermore, an even higher level of accuracy and consensus on the results could, for instance, be obtained by combining the BWM with a (multi-round) Delphi method. A last recommendation for future research is to study the general applicability of the developed BWM model and respective results to PI hubs in general, other than maritime ports.

Appendix 3.A: List of expert interviewees

Table 3.A: *List of expert interviewees*

Function	Affiliation
Professor	Erasmus University Rotterdam
Strategic Initiatives	Fraunhofer
Professor	Georgia Institute of Technology
Professor	Kedge Business School
Professor	Kuehne Logistics University
Professor	Mines Paris Tech
Head of Strategy & Analytics	Port of Rotterdam
Strategist	Port of Rotterdam
Senior Research Scientist	TNO
Professor	University of Groningen

Appendix 3.B: List of BWM survey respondents

Table 3.B: *List of BWM survey respondents*

Function	Affiliation
Senior advisor	ALICE (Alliance for Logistics Innovation through Collaboration in Europe)
CEO	Consulting company
CEO	Consulting company
Professor	Delft University of Technology
Professor	Delft University of Technology
Researcher	Delft University of Technology
Senior Director	European Inland Waterways Platform
Strategic Initiatives	Fraunhofer
Professor	Georgia Institute of Technology
Researcher	Georgia Institute of Technology
Researcher	Georgia Institute of Technology
Researcher	Georgia Institute of Technology
Researcher	Georgia Institute of Technology
Researcher	Georgia Institute of Technology
Researcher	Georgia Institute of Technology

Researcher	Georgia Institute of Technology
Researcher	Georgia Institute of Technology
Business Consultant	Globally leading LSP
Transportation Network Planning Manager	Globally leading LSP
Senior Manager Transport & Logistics	GS1
Supply Chain Manager	Heineken
Professor	Kedge Business School
Professor	Kuehne Logistics University
Professor	Kuehne Logistics University
Head of Innovation	Port of Algeciras
Innovation Manager	Port of Barcelona
Head of Strategy & Analytics	Port of Rotterdam
Strategist	Port of Rotterdam
Research Fellow	Procter & Gamble
Director	Transport Systems Catapult
Professor	University of Groningen
Professor	University of Groningen
Researcher	University of Groningen
Professor	University of Melbourne

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4 An information architecture to enable track-and-trace capability in Physical Internet ports

Fahim, P.B.M., An, R., Rezaei, J., Pang, Y., Montreuil, B., & Tavasszy, L. (2021). An information architecture to enable track-and-trace capability in Physical Internet ports. Computers in Industry, 129, 103443.

Abstract: The Physical Internet (PI), a new vision for the future of the global freight transport and logistics system, describes a geographical hierarchy of interconnected networks of networks, from the urban, to the national, the continental, and the global level. Like today, in PI the maritime ports will fulfil roles as continental and global hubs. Differently than ports today, however, decisions to split and bundle cargo across ships and other modes will not be made solely on the basis of long-term agreements by ports, but rather ever more dynamically and in real-time, aiming to reconsolidate shipments within the port area. This implies a need to reconsider the currently used information systems (ISs), and to gain understanding of future requirements to satisfy their needs. We exploit a design science research (DSR) approach to shape these requirements. Among the many components of future ISs, we study ports' track-and-trace (T&T) capability. The proposed information architecture (IA) enables to integrate T&T capability in PI ports by means of information carried on PI containers into the logistics chain via an open interface platform, which also supports interoperability among the various actors' ISs. The design is based on the Reference Architecture Model for Industry 4.0 (RAMI 4.0). This model supports the analysis of PI ports in key dimensions along with hierarchical logistics entities, which could be used as a blueprint for IAs of PI ports, globally. We provide insights into the approach's applicability by means of the illustrative case of Teesport, located in Northeast England (United Kingdom).

4.1 Introduction

Throughout the past centuries, the facilitation of international trade has made significant contributions to the current level of globalization, as well as to global welfare and economy. Current global maritime trade volumes surpass 10 billion tons annually, while 80 % of the total world merchandise trade is transported over sea (Hoffmann et al., 2018). Being the gateway between land and sea, maritime ports function as critical enablers of international trade and global supply chains. Ports can be regarded as dynamic andorganic systems in national socio-economic-political systems as well as in the globalized economic system (Haraldson et al., 2020). Therefore, ports continuously need to evolve by adapting to their external environment in terms of changing economic and trading patterns, new technologies, legislation, and port governance systems.

A system innovation that is already impacting the current economic and trading patterns, technologies, legislation, and governance systems, is the Physical Internet (PI). In 2011, Montreuil (2011) introduced the vision of the PI as one of an open global freight logistics system founded on physical, digital and operational hyperconnectivity through encapsulation, interfaces, and proto-cols. The PI proposes physical packages to be moved similarly tothe way data packets move in the Digital Internet (Pan et al., 2017). In the PI, goods are encapsulated in modularly dimensioned easy-to-interlock intelligent containers, called PI containers, which are designed to optimally flow in hyperconnected logistics networks (Sallez et al., 2016). The PI is expected to strengthen the economic, environmental, and societal sustainability and efficiency of global logistics (Montreuil et al., 2012).

To help achieve hyperconnectivity in the global freight logistics system, ports need to be capable of autonomously routing shipments of PI containers, based on appropriate real-time information availability. Future PI applications will be data intensive and will require strong sensing, communication, data processing. and decision-making capabilities. In the design of intelligent systems, sensing (information handling), which is the focus of ourstudy, comes prior to thinking (problem notification), and acting (decision-making) (Meyer et al., 2009). In PI applications, we consider sensing as the process of achieving increased visibility by means of enhanced track-and-trace (T&T) systems, supported by information architectures (IAs) that allow for communication among the various internal and external logistics entities and actors. A primary means to create visibility of shipments for the complete logistics chain is the T&T capability in ports (McFarlane et al., 2016). PI ports will need to be able to process information on an individual shipment level to facilitate optimal (un)loadingand de- and (re-)compositioning operations of PI containers. This implies that data about the shipments within containers will need to be accessible. In addition, Calatayud et al. (2019) emphasize the importance of T&T systems for predictive decision-making capabilities of supply chains. We argue that in the PI, this importance will grow further and require access to more detailed information. In the PI context, T&T is the real-time ability to locate every individual PI container with its contents and to provide traceability information (e.g. weight, state, commodity type, estimated arrival and depar-ture times, origin and destination, and environmental conditions) to relevant actors (Sallez et al., 2016). Today, however, port information systems (ISs) only support T&T at container level, typically 20 and 40 foot containers, and not at the level of underlying shipment units. If ports want keep an essential existence in the future door-to-door PI system, they should adapt to the needs of the PI and extend the capabilities of the T&T systems. Until now, there has been no attention in the literature on this problem.

To help filling this gap in literature, our research question is the following:

What is the proper arrangement of information flows on shipments and their characteristics, that supports T&T of goods inside a port, within the PI context?

In order to answer this research question, we use a design science research (DSR) approach (Weber, 2018), by the guidelines of which we develop a functional design of an IS that provides the port with the required T&T capabilities (i.e. including shipment level information). The task of re-designing ports' ISs to suit a new functionality is not trivial. Within an IS, the different aspects of information sharing, including data elements, message formats, communication lines, should be defined in line with the new business objectives, and in a consistent relation to each other (Romero and Vernadat, 2016). In this study, we develop such a design. Therefore, our main contribution is the tractable and reproducible designof an IA for the T&T functionality of maritime ports in a PI con-text. The design of a shared information environment that lives up to these conditions is called an IA (Yaqoob et al., 2017). To keep the different aspects of the information tractable, consistent and complete, we use a reference architecture model (RAM) forthe IA design, which provides guidance relative to the different elements that need to be included. A RAM can be defined as anabstract system framework that contains a minimal set of unifying concepts, axioms, and relationships to understand the interactions between entities in and with its environment (Van Geest et al., 2021). We use the Reference Architecture Model for Industry 4.0 (RAMI 4.0), a well-known reference model used worldwide for IA designs (Bangemann et al., 2016). As such, our main research con-tribution is the tractable and reproducible design of an IA for the T&T functionality of maritime ports in a PI context. The rest of the paper is built up as follows. An overview of the relevant port, PI, and IA literature is provided in Section 4.2. Section 4.3 introduces the methodology. Section 4.4 presents a real-world case, which is followed by conceptual design of the IA in Section 4.5. Section 4.6 provides a discussion, while Section 4.7 presents the conclusions of our work and recommendations for future research.

4.2 Literature review

T&T has been recognized as an important element within supply chain management in general, and ports in specific. One stream of literature addresses this from a descriptive port evolution perspective; another from a normative design approach focusing on the global PI as an ultimate vision. In addition, these two streams of literature, we review the literature of innovative RAMs and IAs and their applications, which also include Internet-of-Things (IoT) and blockchain application, designed for the Industry 4.0 movement. We conclude this section by identifying a converging research gap as the starting point for our work.

4.2.1 Maritime port evolution and developments

In the maritime port logistics literature, the evolutionary path of ports has been described through several generations (Lee and Lam, 2016). Ports, over time, have evolved from first generation ports (1GPs), which merely served as gateways between land and sea, and are now moving into fifth generation ports (5GPs), which are considered highly complex and dynamic multi-actor systems with advanced (information) technologies and a wide range of (value-added) services, in addition to the traditional ones. Lee and Lam (2016) emphasize the key roles of new information technology (IT) in the most modern 5GPs, notably contrasting their IT features versus those of fourth-generation ports (4GPs). Essentially, IT in 4GPs focuses on providing cargo clearance and T&T serviceson container level, whereas IT in 5GPs goes one step further by offering its users a single window (SW) by means of Port Community Systems (PCSs) for information exchange about T&T of notonly maritime containers but also its contents (on a shipment level), delivery information, and performance measurement (Lee and Lam, 2016). Another more recently developed concept that explains current and future practices, and is closely linked with PCSs, is Port Collaborative Decision-Making (PortCDM).

By making the foreland operations as predictable and real-time as possible, PortCDM makes not only processes in one port more efficient, but will also contribute to an increase in the efficiencies of other ports and vessels (Lind et al., 2020).

A distinction can be made between internal T&T systems inside a particular (local) logistics system, such as a port, and external T&T systems across the supply chain. In 5GPs, PCSs fulfil the function of, among others, T&T across the supply chain (EPCSA, 2011a). A PCS can be defined as a neutral and open electronic platform, enabling intelligent and secure exchange of information between public and private actors to improve the competitiveness of port communities (EPCSA, 2011b). PCSs aim to contribute to optimizing, managing, and automating port and logistics processes through a single submission of data and connecting supply chains (IPCSA, 2018). Globally, various PCSs with a range of functionalities have emerged over the years (e.g. Dakosy in Germany, Logink in China, Maqta in United Arab Emirates, Portbase in the Netherlands). In addition, initiatives are being taken to expand the knowledge capacity and enhance usability of these systems among its actors, often led by the European and International PCS Associations (EPCSA and IPCSA), and United Nations. In line with the objective of the PI becoming an open global freight transport and logistics system through physical, digital and operational hyperconnectivity (Montreuil, 2011), future PCSs aim to support T&T capabilities and interoperability across supply chains (UNESCAP, 2018). However, the PI has not been considered in the PCS literature whatsoever. The requirements of the PI concerning T&T capabilities of a port should be known to be able to develop PCSs in line with the 5GP vision.

4.2.2 Physical Internet (PI)

Montreuil (2011) defined the vision of the PI as an open logistics system that is capable of being accessed by all actors in a logistics chain at a global scale. Montreuil et al. (2012) suggest a framework of PI foundations representing the PI’s building blocks and their systematic relationships, organized in layers, including commodities, shipments, load units, carriers, and infrastructure networks. At the core of the PI are the fundamental goals of improving economic, environmental, and societal efficiency and sustainability (Ballot et al., 2014). To achieve these goals, hyperconnectivity at the physical, digital, operational, transactional, legal, and personal levels is a prerequisite (Montreuil et al., 2016). This hyperconnectivity is enabled by three key PI features: encapsulation, interfaces, and protocols (Montreuil et al., 2013).

Encapsulation

The PI encapsulates freight into modular (PI) containers that are easy to handle, store and transport, smart and connected, and eco-friendly (Montreuil, 2011). Montreuil et al. (2016) propose a three-layer typology of PI containers: packaging containers (P-containers), handling containers (H-containers), and transport containers (T-containers). P-containers directly enclose and protect the physical objects in the innermost composition. P-containers can be embedded in H-containers designed for use in handling and operations within the PI. H-containers can be embedded inT-containers, which are functionally similar to the maritime shipping containers that are currently used, exploitable across multiple modes of transportation.

Interfaces

In order to provide transport and logistics services, the PI system needs to consider both physical (operational) interfaces as well as information and communication (I&C) interfaces, as emphasized in Montreuil et al. (2012) and synthesized in Table 4.1. The interactions and the exchanging data sources between the two interfaces provide the new context for increasing the visibility in transport chains. While the high-level interfaces focus on logistics services, the low-level interfaces focus on the PI containers at which the information is carried.

Protocols

The PI enables the interconnected exploitation of logistics networks through cooperative protocols agreed upon and exploited by the variety of actors in the logistics chains. PI protocols not only ensure the integration of logistics entities but also their performance, resilience, and reliability in PI networks (Montreuil, 2011). Standardized PI routing protocols will facilitate dynamic routing of PI containers across multiple modes of transport in the PI 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 as the PI’s equivalent to the Open Systems Interconnection (OSI) model, the ISO’s networking model. Figure 4.1 depicts the OLI model with its seven layers and respective protocols. The layered protocols of the OLI model provide a framework for exploiting physical, digital, financial, human, and organizational means of the PI (Ballot et al., 2014). On each layer, an instance provides services to an instance on a higher layer, while receiving services from an instance on a lower layer. Simultaneously, instances on the same layer can also provide and receive services to and from each other. Note that, from the OLI perspective, a T&T functionality within a port will primarily conduct the operations within L1, L2, and L3, while supporting routing and shipment decisions at L4 and L5. A port, as a hub, allows for routing decisions, the rearrangement of products by means of PI containers, and their assignment to service classes. In line with the OLI, the to be designed IA considers how data is transmitted between different layers.

Table 4.1: *Types and levels of interfaces*

Type of interface	**Level of interface**	**Interface**
Physical (Operational) Interfaces	Low	Complementary physical fixtures that allow PI containers to interlock with one another, and to be snapped to storage structure.
	High	Logistics PI-nodes that are available for smooth logistics services (e.g. transfer from unimodal to multimodal transportation) by appropriately allocating freight within the PI network.
Information & Communication (I&C) Interfaces	Low	Smart tags on PI containers capable of identification, routing, traceability, conditioning of each modular container.
	High	Digital middleware platforms that provide an open market for logistics services in PI by connecting human and the PI's components.

Containers

From a PI container perspective, Sallez et al. (2016) exhibited its role in hyperconnected PI networks. They identified four categories to classify PI container users in a logistics chain. A simplified logistics chain of a PI container includes these users: shippers and receivers, PI transport service providers, PI hubs, PI coordinators. Following this categorization, maritime ports can clearly be categorized into the PI hub category, whereas, based on the earlier provided definition and description of PCSs, these could be a strong candidate for the role of a PI coordinator. Furthermore, Sallez et al. (2016) listed identification, T&T, state monitoring, data compatibility and interoperability, and confidentiality as informational aspects of PI containers. Smart containers have an embedded set of sensors, enabling it to communicate real time information with its users on location, door opening and closing, vibrations, temperature, humidity, and any measured physical parameters of the surrounding environment (Becha et al., 2020). Although our primary focusis on T&T systems inside the port, the other informational aspects are important to consider as well. The Modulushca project was the first project on a European level that endeavored to contribute tothe realization of the PI by focusing on the development of a set of exchangeable modular logistics units, i.e. PI containers, in the fast-moving consumer goods industry (Modulushca Project, 2017).

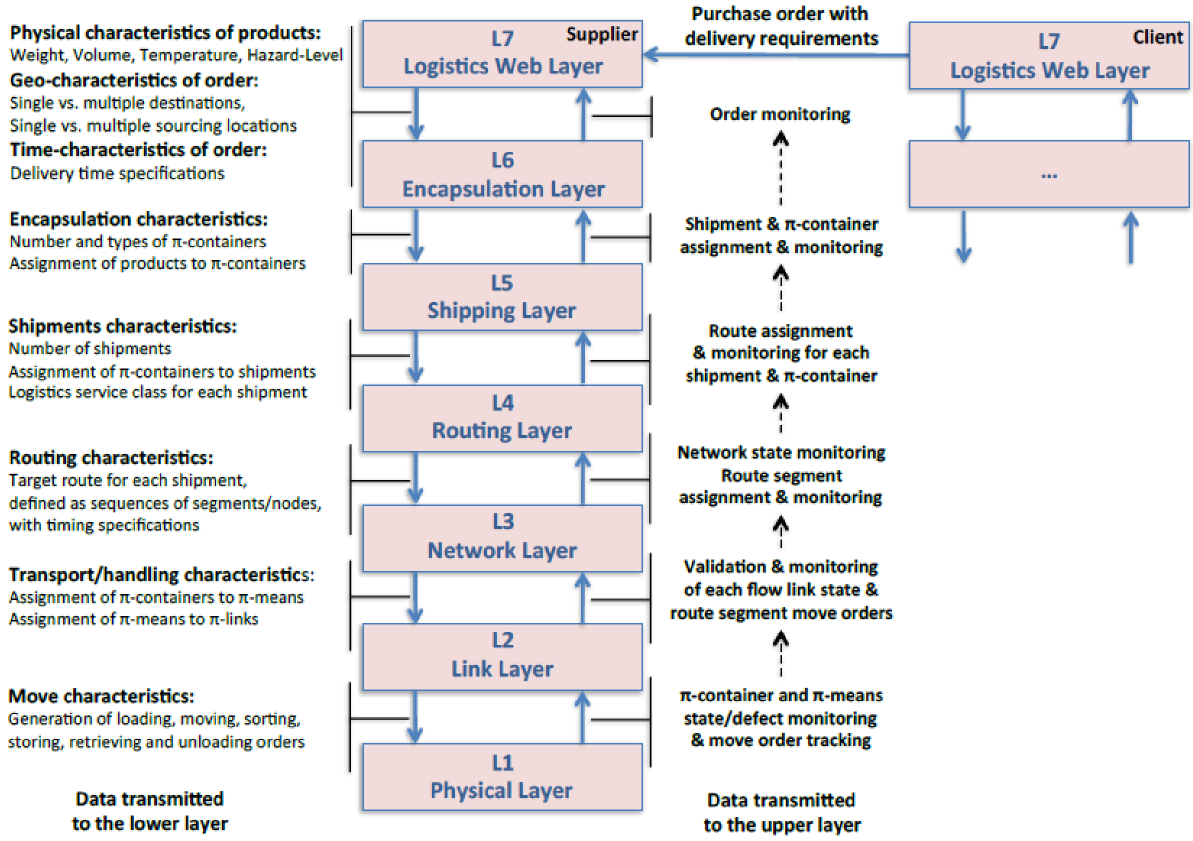

Figure 4.1: The seven-layer OLI model with respective inter-layer service description (adopted from: Montreuil et al., 2012).

Hubs

From the perspective of PI hubs, Ballot et al. (2012) and Meller et al. (2012) propose functional designs of a road-rail hub and a road-based transit hub, respectively. Ballot et al. (2014) present some generic designs of uni- and multimodal hubs, and road and rail hubs, while Sallez et al. (2015) proposed a hybrid control architecture for the routing of PI containers in road-rail (cross-docking) PI hubs. Walha et al. (2016) investigated an allocation problem in the context of the PI with the objective to improve rail-road PI hub efficiency by optimizing the travelled distances. Summarizing, Montreuil et al. (2018) more recently argued that exploiting hyperconnectivity and modularity provides seven fundamental transformations to parcel logistics hub design: (1) hubs are to receive and ship modular containers encapsulating parcel consolidated by next joint destination; (2) hubs are to exploit pre-consolidation; (3) hubs are to have less direct sources and destinations as the current; (4) hubs are to be ever more multi-actor and multi-modal service providers; (5) hubs are to be more agile through real-time dynamic and responsive shipping times; (6) hubs are to be capable of conducting smart, real-time dynamic decisionson the container consolidation and internal flow orchestration; and (7) hubs are to be active agents in the PI network, dynamically exchanging real-time information on the status of parcels, containers, vehicles, routes, and the other hubs.

For a more comprehensive review of the PI literature, we refer to Treiblmaier et al. (2020).

4.2.3 Information Architectures (IA)

More recently, with the introduction of Internet-of-Things (IoT) and blockchain as enablers for a wide range of applications in logistics and supply chain management (Galati and Bigliardi, 2019), various IAs have been proposed with specific applications (Yaqoob et al., 2017). Bisogno et al. (2015) created an integrated information flows model for PCS to improve intelligent logistics services by means of adopting a case study approach, investigating the Port of Salerno. Li et al. (2016) argued that in current logistics, there is a lack of devices that can effectively provide visibility on real-time in-transit information of container freight. Hence, they constructed a T&T device architecture based on IoT technology in combination with a multi-sensor device to provide real-time in-transit visibility. Tian (2016) studied the utilization of radio frequency identification (RFID) and blockchain technology in building an agri-food supply chain traceability system. They developed a system that realizes traceability with trusted information, which would effectively guarantee the food safety by gathering, transferring, and sharing data in production, processing, warehousing and distribution. Raap et al. (2016) proposed an architecture for an integration platform that supports the automated collection of real-time container tracking data for the purpose of more efficient planning by LSPs. Byun et al. (2017) developed a system architecture that contributes to their graph-oriented persistence approach to achieve efficient and privacy-enhanced object traceability based on unified and linked electronic product code information services. Betti et al. (2019) and Hasan et al. (2020) both focused on exploiting blockchain within a PI context. While Betti et al. (2019) proposed smart contracts to improve PI trustability and cybersecurity, Hasan et al. (2020) presented two permissioned blockchain architectures that provide decentralization, privacy, trust, immutability, and transparency in PI networks. Also in the food supply chain area, Mondal et al. (2019) proposed a blockchain inspired IoT architecture for the purpose of enhancing transparency. The architecture was based on the integration of RFID-based sensor at a physical layer, while applying blockchain technology at the cyber layer. Van Geest et al. (2021) presented a generic business process model for smart warehouses, while simultaneously modelling its reference architecture.

The IS literature has recently evolved in terms of providing RAMs for innovative IA designs. Similar to the PI, Industry 4.0 has the potential to impact entire industries by transforming the way goods are designed, manufactured, delivered, and paid (Hofmann and Rüsch, 2017). They both integrate cyber-physical systems in the production and logistics domain and the use of web-based services in industrial processes (Galati and Bigliardi, 2019). Lasi et al. (2014) and Boyes et al. (2018) argue similarly that Industry 4.0 demands architectures which support its implementation in different areas, from the design of products to the distribution with the participation of actors connected by a collaborative network in a distributed environment. Weyrich and Ebert (2015) propose five RAMs that are suitable for IoT applications: RAMI 4.0; Industrial Internet Reference Architecture (IIRA); IoT-Architecture; Standard for an Architectural Framework for IoT; and Arrowhead Framework. Although each of the RAMs has its merits, RAMI 4.0 provides the extended ability to focus on multiple system layers, while considering hierarchical levels, life cycles and value streams (Pisching et al., 2018). In addition, RAMI 4.0 allows for the description and implementation of highly flexible concepts in a standardized way, whereas other RAMs have a strong focus on specific use cases (Adolphs et al., 2015). In essence, RAMI 4.0 provides a “basic reference architecture” for Industry 4.0

(Bangemann et al., 2016), and hence, many major companies and institutions in various industries use RAMI 4.0 (Weyrich and Ebert, 2015).

4.2.4 Literature gaps and contribution

The literature on maritime ports and cargo hubs is starting to recognize the importance and complexity of the exchange of data across actors to serve the users of the port (Watson et al., 2020). Additionally, IT has been recognized as an enabler for port users to securely exchange data and provide visibility to the benefit of the actors and operations throughout the logistics chains. Although designs of ISs are emerging to serve new needs in ports, such as for synchronization of containers' movements across modes (Raap et al., 2016), we observe that there still is a general paucity of IS research and literature on the (maritime) shipping industry. In addition, although research within the PI has been moving towards design-oriented work, current works are notably on the physical layout and activities of PI hubs and to a much lesser extent on their IA, where more recent research of Betti et al. (2019) and Hasan et al. (2020) can be counted as exceptions. They do not design for the T&T functionality explicitly, however. We conclude that an IA for maritime PI ports, with a focus on T&T to support global hyperconnectivity at a PI container level, is still lacking. By means of designing a tractable and reproducible IA for the T&T functionality of maritime ports in a PI context in this paper, we aim to contribute with a first step towards a solution to this problem and filling the aforementioned gaps in literature.

In the next section, we introduce our main approach. In a DSR context, we design an IA for the T&T function of PI ports. The use of a RAMI 4.0 allows us to consider several layers and hierarchical levels in IS design, from assets providing the data to the functional level of information exchange between actors. We use an illustrative case of a real-world logistics chain to show the practicability of the design approach, notably in deriving requirements.

4.3 Methodology

The design of an innovative PI T&T IA preliminarily aims to achieve appropriate PI container information accessibility, quality and usefulness through open interfaces and global protocols. Port ISs need to process T&T information on PI container level to facilitate effective, dynamic and real-time (un)loading, de- and (re-)compositioning of containers at ports. Using design as research activity implies a DSR approach, in contrast to the classical research approach focusing on theory development and testing.

The focus of the design problem is summarized in Figure 4.2. The PI has a well elaborated system architecture, the OLI model, relating to the activities, decisions and components underlying the demand for, and delivery of, freight transport services. This domain model of the PI also specifies an information need. The IA for the system to satisfy this need can be designed based on a RAM, by defining the components of the model in the domain context. Together, these sketch the design problem, where our focus lies on the design of the PI Port T&T IA.

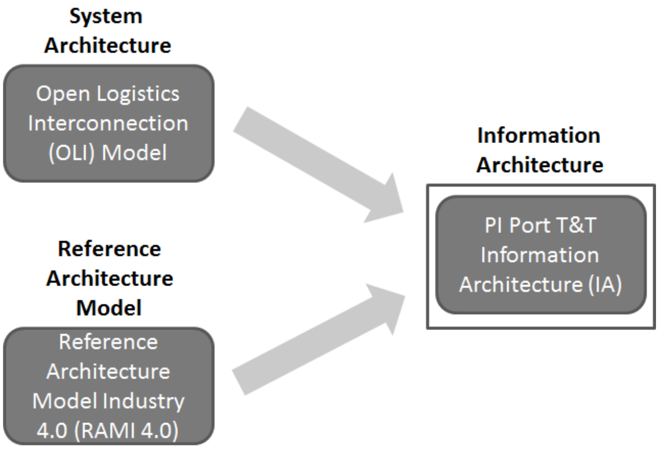

Figure 4.2: *Design Focus*

4.3.1 Design Science Research (DSR)

Research within the field of ISs is considered to be a discipline that combines technical research on IT, the application and business uses of IT, as well as its natural, social, and behavioural scientific dimensions (Gregor and Hevner, 2013). According to Weber (2018), within the IS research discipline, traditionally there are two types of research: (1) classical research, and (2) DSR. The classical type of research focuses on building and testing theories, while DSR focuses on building artefacts that could be useful to a particular actor community. DSR has its roots in engineering and fundamentally works according to a problem-solving paradigm (Baskerville et al., 2018). DSR involves the construction of a wide range of socio-technical artefacts, such as decision support systems, modelling tools, methods for IS evaluation and change intervention, and governance strategies (Gregor and Hevner, 2013). According to Hevner (2007), every DSR project should have (1) its problem, (2) its (benefitting) environment, (3) the to be designed artefact, and (4) clearly identified and defined contribution to knowledge. Baskerville et al. (2018) summarize that the DSR paradigm combines practical relevance and scientific rigor to IS research, through its emphasis on designing useful artefacts and formulating design theories. In line with Haraldson et al. (2020), we argue that the freight transport and logistics system can be considered as a large-scale socio-technical system that consists of various functional subsystems and operates in a complex environment, which correspondingly includes a large set of participating actors. Our research can be positioned in the light of the four main DSR elements of as follows:

1. The *problem* is that current IS of ports are not able to provide the necessary visibility and interoperability, in terms of T&T of logistics operations, to fully operate in a hyperconnected PI network with its modular PI containers.
2. The *(benefitting) environment* consists of actors in the logistics chain that are involved in the shipping and trading of goods. As summarized by Sallez et al. (2016), these actors can be categorized into: *shippers and receivers, transport service providers, hubs,* and *coordinators.*
3. The to be designed *artefact* is an innovative IA, which is based on the RAMI 4.0, for the T&T function of maritime ports in the PI. A suitable way to test the application of RAMI 4.0 is through a use case (Adolphs et al., 2015). Hence, to keep the design rooted in a real-world situation, in Section 4.4, we show the applicability of the to be designed artefact through an illustrative use case.
4. The main *contribution to knowledge* of our research is the design of a tractable and reproducible IA for the T&T functionality of maritime ports in a PI context.

4.3.2 Reference Architecture Model for Industry 4.0 (RAMI 4.0)

As mentioned earlier, in a similar manner as the PI, Industry 4.0 has the potential to impact entire industries (Oesterreich and Teuteberg, 2016). In line with Industry 4.0, RAMI 4.0 was introduced by Adolphs et al. (2015). In RAMI 4.0, the design of objects of the physical and digital world are combined into a holistic approach by means of different layers. It structures existing standards, identifies missing (links between) standards, and highlights areas that need standardization (Weyrich and Ebert, 2015), while overlaps and redundancies become visible and open to discussion (Adolphs et al., 2015).

As can be observed from Figure 4.3, RAMI 4.0 comprises three dimensions that are used to view one particular (sub)system from different angles (Fleischmann et al., 2016):

- *Layers* separate the concern of interoperability, and understanding of syntax and semantics from different views. Also, the layers serve as interfaces between the physical and digital world.
- *Hierarchy Levels* enable a functional allocation of (sub)system components, and therefore, this dimension can be used as a guideline to allocate the different modules of a system. From the perspective of this dimension, the RAMI 4.0 derives its classification from the IEC 62264 and IEC 61512 standards.
- *Life Cycle & Value Stream (LC&VS)* allows the classification of a particular state in which the (sub)system currently finds itself in the LC&VS. From the standardization perspective of this dimension, the RAMI 4.0 derives the LC&VS from the IEC 62890 standards.

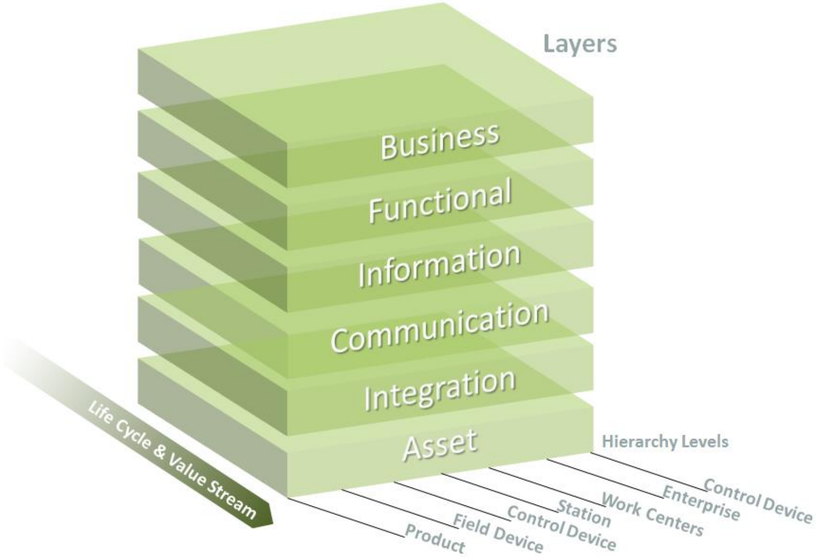

Figure 4.3: *Reference Architecture Model for Industry (RAMI) 4.0 (adapted from: Adolphs et al., 2015)*

4.3.3 Scoping of RAMI 4.0 for the design problem

Firstly, when considering the three dimensions of the framework, our focus will lie on the *Layers* and *Hierarchy Levels* dimensions for designing the RAM of a PI port's T&T system under practical conditions. Although the dimension of *LC&VS*, which concerns itself with the dynamic process of migration and implementation from the world of today into that of the future, is a significant one, our primary objective is to propose a design for an IA of the T&T system of PI ports. Hence, we will consider the single and constant point in time of an implemented PI.

Secondly, although the *Communication and Integration Layer* are included in the RAMI 4.0, these mainly concern the IT technologies that combine and transmit information from the *Asset Layer* into the *Information Layer*. It is at this level that technological options such as blockchain enter the design of the system. In our design, however, we make the choice to abstain from specifying these technologies, as we believe that these choices are not essential to sketch the functionality of the IS, and will even distract us from doing so. For readers that are interested in these specific two layers in a logistics context, we refer to Li et al (2016). The emphasis of our paper lies on the design of the *Asset, Information, Functional, and Business* layers of the IA.

4.4 Teesport as illustrative use case

In the previous section, we introduced RAMI 4.0 to design an IA for PI ports' T&T systems. In this section, we introduce the Teesport as an illustrative use case through which we aim to show the applicability of our methodology. In addition, we aim to derive requirements from the Teesport case to use for the conceptual design of the IA of the T&T system in the next section. Teesport can be considered as an example of the Port Centric Logistics (PCL) paradigm. PCL can be defined as providing value-added services (VAS), such as product localization, warehousing and distribution, labelling, quality inspections, light manufacturing and final assembly, within port perimeters (Monios et al., 2018). Integrating VAS at ports enables logistics networks to be less complex and, among others, removes the necessity of making an extra stop at other dedicated logistics centers. PCL has been argued to be the main concept of the next generation (in the evolution) of ports (Monios et al., 2018). From this perspective, PCL can be regarded as an early generation PI port, which is expected to be an increasingly dominant, active and intelligent agent in the logistics chain through the dynamic exchange of goods and information with its actors (Montreuil et al., 2018). We investigated the concept of PCL and its current practical implementations to understand potential useful contributions of the three PI components of (1) encapsulation, (2) interfaces, and (3) protocols. Encapsulation through modularization is expected to, among others, contribute to decreasing the number of used containers through improved space utilization. By the use of interfaces and standard protocols (in T&T systems), both visibility of PI containers in- and outside the port, and interconnectivity between ports, and between ports and other actors in the logistics chain are expected to be enhanced.

4.4.1 Position of Teesport in the logistics chain

Figure 4.4 shows that Manufacturer X, which is a Shanghai based T-shirt and swimsuit manufacturer, and Manufacturer Y, which is a Hong Kong based television manufacturer, ship their products through the Port of Shanghai and Port of Hong Kong, respectively, by means of maritime container transport to Teesport, the port of discharge. Once arrived at Teesport, the shipments will be repositioned according to their next or final destination, as for example the Retailer's distribution center (DC), and will continue their journey.

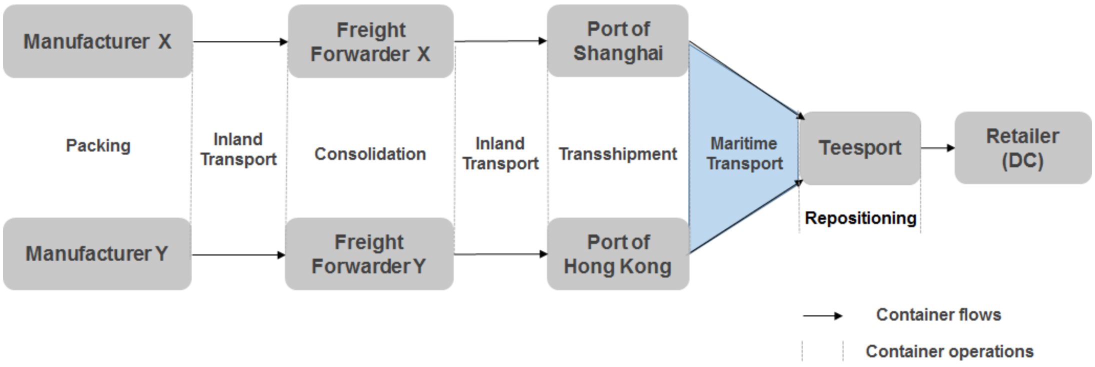

Figure 4.4: *The logistics chain of the Teesport case*

4.4.2 Envisioned operations at Teesport

Figure 4.5 shows a more detailed schematic of an example of envisioned decompositioning and (re-)compositioning operations at Teesport. Two T-containers arrive at Teesport from the Port of Shanghai and Port of Hong Kong. As indicated by the orange, green, and blue rectangles, once the *inbound T-containers* arrive at Teesport, they are decomposed in the *Decomposition* phase. Next, P-containers and H-containers, are, again, composed (or consolidated) into H-containers and T-containers in the *(re-)Composition* phase according to their optimal routing and consolidation opportunities, which are determined, among others, by the variables of final destination and desired time-window. Here, P-containers and H-containers are composed into a T-container in such a way that space is optimally utilized, and they are ready to be dispatched to the retailer's DC. In the meantime, the "left over" P-containers and H-containers are stored until there are enough for a next destination in a desired time window to be consolidated and dispatched.

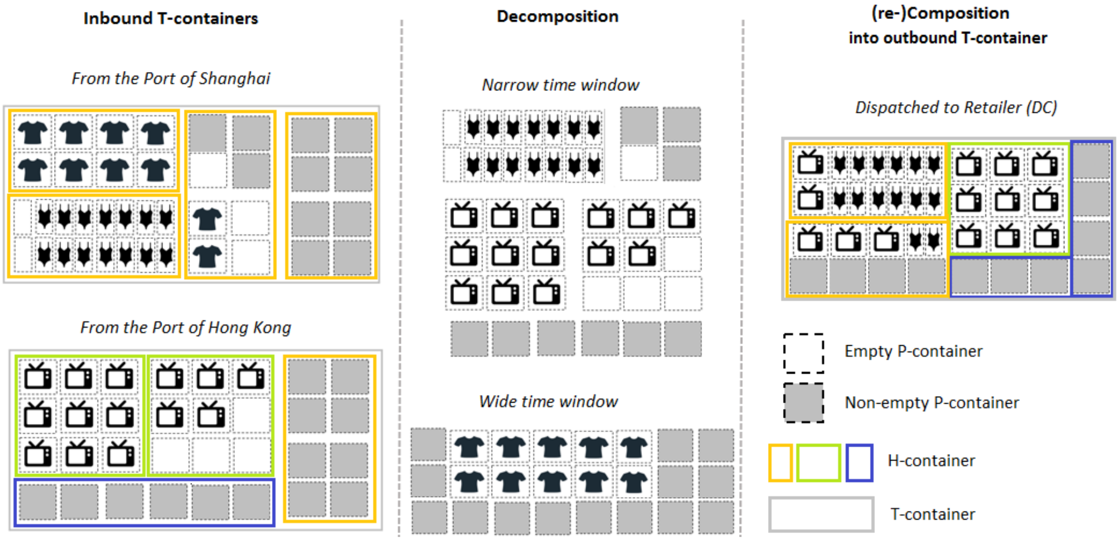

Figure 4.5: *Decompositioning and (re-)compositioning operations at Teesport*

4.4.3 Envisioned T&T system

When we consider the Teesport case, we argue that, by implementing the proposed IA, enhanced visibility will be gained on the two inbound containers by means of the T&T system, through being able to access local and global data which has been provided by logistics actors through the PI's Open Interface (PI OI). This data allows Teesport to plan its operations in advance and dynamically according to the optimal container (re-)configurations before outbound dispatching. Modular P/H/T-containers might, for example, have changing states, routes, and estimated departure and arrival times. In addition, in terms of enhanced interconnectivity, changes in relevant local and global data are required to be detected by Teesport's T&T system and shared with other relevant actors in the logistics chain (e.g. vessels, shipping lines, transport suppliers, consignees) through the PI OI.

The following requirements for PI ports and its T&T system can be derived from the Teesport case:

- The port needs physical and digital accessibility on all three tiers of modular containers to increasingly become a dominant, active and intelligent agent in the logistics chain through the dynamic exchange of goods and information;
- The port needs to be able to retrieve high quality and useful data (e.g. weight, state, commodity type, estimated arrival and departure times, origin and destination, and environmental conditions) about the incoming shipments to be able to determine optimal (re-)compositioning configurations for the utilization of space, considering optimal routes and delivery time windows; and
- The port needs to have real-time access to both local and global data on modular PI containers in the PI OI, and vice versa.

4.5 Conceptual design

After having introduced the methodology in Section 4.3 and having presented the illustrative Teesport case in Section 4.4, this section proposes the conceptual design of the PI Port T&T IS' IA. However, to support this design, we first define a minimal scope for our IA design which obviates the definition of specific technologies for hardware and software.

4.5.1 Design scoping in relation to the full RAMI 4.0 framework

In line with the scoping of our research in Section 4.3, inspired by Fleischmann et al. (2016), our design will operationalise a reduced version of RAMI 4.0 (see Figure 4.6), which includes the dimensions of Layers and Hierarchy Levels. As we want to emphasize the exchange of information and stay clear from a discussion of specific technologies to store and exchange information, our focus is on the design of the *Asset, Information* and *Functional* layers of the IA, given the needs identified in the *Business Layer*. We argue that our design is neutral to technology choices made in the *Integration* and *Communication* Layers. In a second-round design, a follow-up on this research will be needed to contemplate alternatives, evaluate them (based on the ability to support this IA and on criteria like technology readiness), and specify these layers in detail.

In this framework, data of the logistics entities for the T&T functionality is acquired on the *Asset Layer*, where the information flows start from. The data is acquired via a low-level interface by means of a *Field Device*, such as smart tags (e.g. RFID). The *T&T Engine* and the *WEB Engine* are also part of the Asset layer. After going through the *Integration* and *Communication Layer*, which allows for the transition from the physical and digital world, on the *Information Layer*, firstly, the internal *local data flows* are acquired by the middleware platform of the high-level interface to support the *PI Port T&T IS*. This can be done by connecting local port entities via local data flows. Secondly, the Port T&T IS enables the exchange of local data flows and external data from *external logistics entities* through collaborative agreements between actors in the logistics chain by means of the *Interconnection module* by exploiting interfaces and standardized PI protocols in the *PI Open Interface* (PI OI). The PI OI represents the interface and interconnection with all other relevant actors in the PI network. The PI containers' T&T information and the interconnectivity of the IS of PI ports are implemented on the *Functional Layer*, which contains all the necessary functions. The highest *Business Layer* contains the overall business model, regulatory framework and respective operations.

We can define four modules along with the hierarchy levels in the adapted version of RAMI 4.0. The *Perception module* serves to perceive local data from the physical (logistics) entities during the operations. The *Processing module* generates the T&T data by means of the *T&T Engine*, whereas the *Human-Machine Interface module* enables the communication with clients by means of a *WEB Engine*. The *Interconnection module* connects the port's IS with external logistics entities' IS by means of the PI OI to facilitate information exchange. The overall function of the four modules determines the information flows of the PI containers' T&T data within PI ports with respect to the four addressed layers within the RAMI 4.0.

Below we describe these four layers to operationalize the depicted reference framework in Figure 6 for our specific purposes, leading to the IA design. In a top-down sequence we describe the Business Layer to have the requirements clear from the PI, and subsequently turn to the Functional, Information and Asset layers.

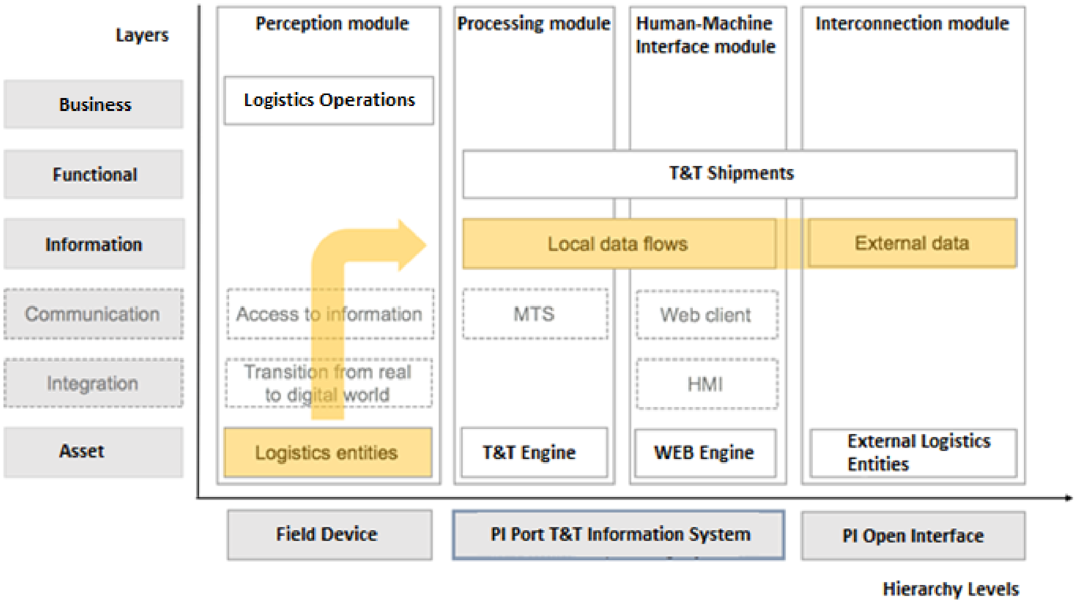

Figure 4.6: *Adapted version of RAMI 4.0 for the T&T system of PI Ports*

4.5.2 Business Layer

The Business Layer refers to the business processes, and describes the logistics operations as would happen in the PI, to have a clear starting point for the design of the underlying information processes. Here, we further build upon the foundations of the business processes and logistics operations that have been illustrated in the Teesport case of Section 4.4. Figure 4.7 visualizes the operational processes of a part of a logistics chain in the PI, using a Business Process Model and Notation (BPMN) diagram that starts at a port terminal and ends at a consignee. A major difference in the processes with the today's situation is the presence of various levels of PI containers (P/H/T-containers) in PI ports. Another major difference, as also illustrated before in the Teesport case, is the absorption of (some of) the VAS, such as decompositioning and (re-)compositioinng of PI containers by PI ports. The blue-highlighted operations in Figure 4.7 specify the new and PI specific operations at the port. The following assumptions hold in this design of the operational processes:

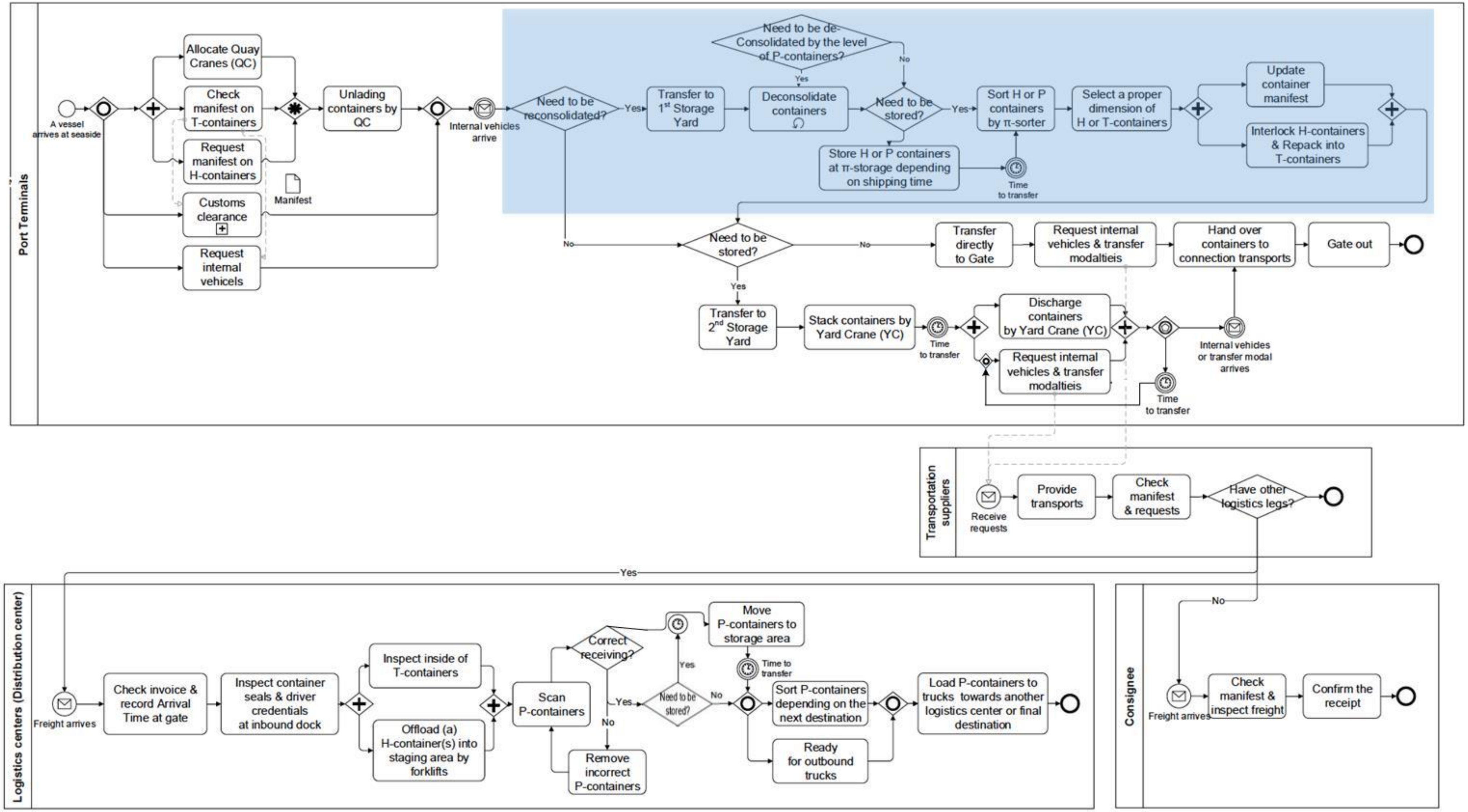

***Figure 4.7:** BPMN-diagram of Envisioned Operational Process from the Business Layer*

- Loading units in PI ports can be P/H/T-containers;
- T&T systems are linked with the PI OI for multilateral information exchange;
- Modular containers are embedded with smart tags capable of providing data to PI ports; and
- The de- and (re)compositioning of PI containers takes place at the port.

Figure 4.7 shows that the business processes include new operational activities related to decision making, the acquisition of decision-making information, and the publishing of updated information that results from the implementation of these decisions. All these serve the de- and recompositioning of PI containers, at different levels of modularity, as the needs arise.

4.5.3 Functional Layer

The *Functional Layer* is a formal description of the information processing functions of the internal T&T functions for the PI containers, together with the interactions with external ISs by means of the PI OI. These functions are derived from the Business Layer, so that in the IA, the model workflows and data flows intersect with logistics activities. The performance of the Functional Layer has a new meaning in PI ports compared to the current systems, as it now also represents the integration between internal T&T systems of PI ports and the PI OI.

This layer is modelled by means of an Activity Diagram, as shown in Figure 4.8. Aiming at the major T&T functions, the figure shows the internal elements of the T&T systems in ports, the external elements of the PI OI, and the user of the PI OI. In addition, it shows the interaction between different elements inside the T&T system and the PI OI, and between these systems. Information flows are used as primary input of these activities and interactions.

As one of the notable differences from the current systems, the Functional Layer of PI ports includes the PI OI. The PI OI comprises three primary components: (1) Database server, (2) Application Programming Interface (API), and (3) Interface (web). Regarding the requests from users, the front-end interface grasps the requests and calls the API to process them with authentication. By request, the API can feed information into the database (DB), or alternatively retrieve information from it. DBs have been simplified in the lane of the DB server as PI DB and user DB. The PI DB corresponds with the DB of the vessel, transportation supplier, PI containers, and transport status. Another difference can be pointed out as a consequence of the intelligence of PI containers. Whereas currently the function of information handling and decision making is distributed over multiple actors in the logistics chain, PI containers will, by means of smart tags, have the capability to collect the relevant information themselves and making their own decisions according to the latest known state of the system (Sallez et al., 2016).

The Functional Layer of RAMI 4.0 has highlighted interoperability between the T&T system and the PI OI with a focus on information exchange. In contrast with the reciprocal communication in current port systems, the PI OI enables all relevant actors to exchange their information in a multilateral manner with the support of an API and DB server. In the next subsection, we describe how data is used to compose the information elements support the Functional Layer.

4.5.4 Information Layer

In the Information Layer, the relevant attributes and operations of shipments are recorded and stored as digital sources and exchanged in data flows. The Information Layer elaborates on the information exchange and the provision of structured data via service interfaces from one entity to another, while ensuring data integrity, consistent integration of data, and obtaining new and high-quality data.

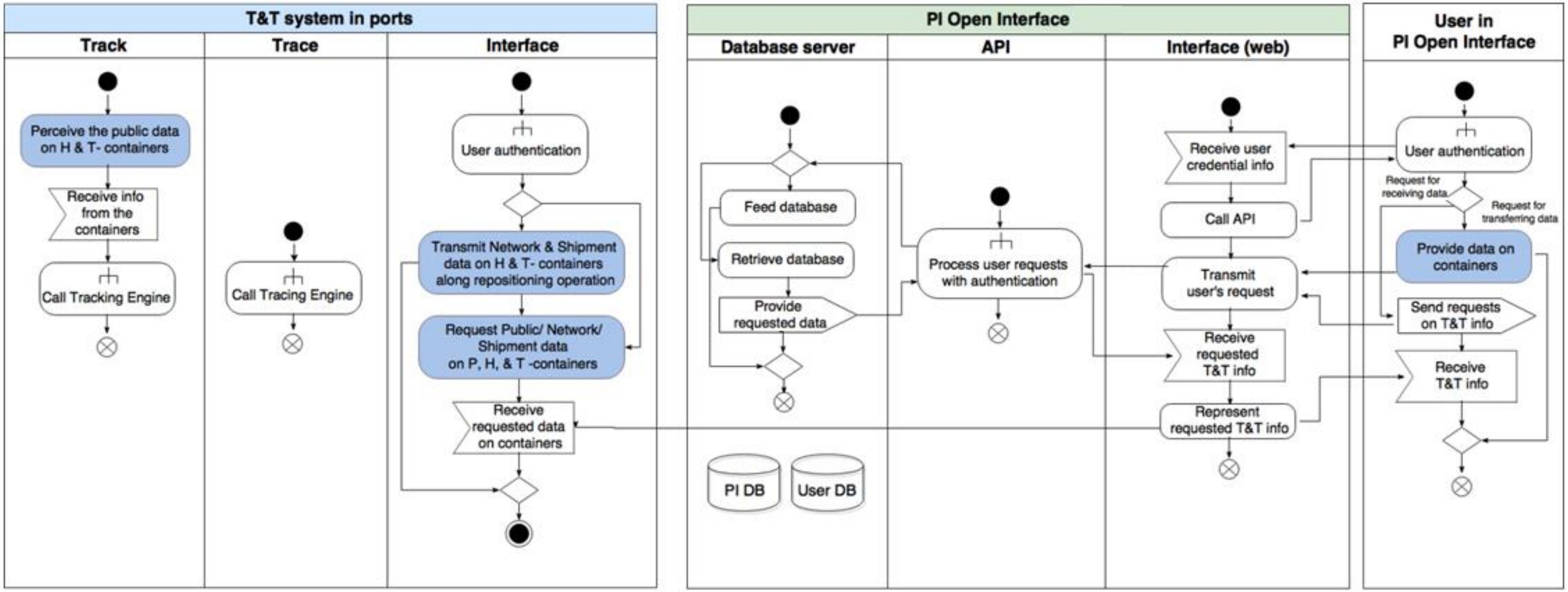

Figure 4.8: *Activity diagram for the Functional Layer of PI Ports' T&T Information Architecture*

Figure 4.9 shows the context diagram of the Information Layer, and provides a formal description of rules and the execution of event-related rules. These rules initiate processing of information in the Functional layer. In our case, local and external data flows between internal and external logistics actors and entities are the main subject of this layer. The data flows reflect the interdependencies between the T&T system of a port, the PI OI (Web Platform), and the other logistics entities. In contrast with current systems, PI ports send user credential information to the PI OI (Web Platform) for authentication and authorization of data, and not directly to other logistics actors in a bilateral manner. In the PI OI (Web Platform), the API authenticates the PI port and retrieves data from the PI OI's DB server. The information from the DB server is transferred the other way around from the DB to the PI OI through the API.

Reflecting on the T&T system, the retrieved information can be used as input for T&T information to for example optimize its decompositioning and (re-)compositioning operations, as also indicated in the Teesport case. The undertaken operations in PI ports can de recorded in the DB of operations. In turn, PI ports' T&T information is also transmitted into the PI OI for the use of external logistics actors and entities. Depending on actors' specific tasks and involvement in a particular shipment's logistics chain, they will receive respective authorization to data in the PI OI. Shippers, for example, can receive the T&T information on all levels of PI containers, in which their shipment is encapsulated. LSPs and transportation suppliers are similarly authorized to all types of T&T information of modular containers, depending on their specific task and involvement in the logistics chain. In contrast, shipping lines mostly deal with T-containers in shipping operations, and therefore, most likely to be authorized to retrieve data on T-container level. Customs agencies will again be authorized to be able to receive the most detailed information about containers on every level.

4.5.5 Asset Layer

The Asset Layer within RAMI 4.0 describes the attributes of the physical assets, such as, for example, components, machines and factories of a system. In our case, it is designed to clarify the characteristics and relationships of logistics entities such as vessels, PI containers and various types of terminal equipment, such as quay cranes, yard cranes, and other internal vehicles. We build on the entities as we envision them in a PI port, to be able to support all the higher-level layers of the AI in a PI context. Assuming that T&T systems of PI ports are interconnected with the PI OI as a web-based platform, ports are enabled to communicate the internal T&T information of PI containers with other logistics actors and entities. Information flows of PI containers fulfil the functions of T&T via the local T&T interface, where the PI DB and the User DB are the intermediate steps of the information flows through the PI OI (see Figure 4.8).

Compared to a non-PI environment, the Asset Layer will need to capture increased interactions in operations and information exchange within ports, as well as new attributes of containers. The Asset Layer reflects the physical difference with current T&T systems through the use of PI containers, which ultimately are expected to contribute to more efficient space utilization, enhanced visibility, and seamless multimodal multi-party flow through enhanced information related to weight, current location, origin and destination, routing, estimated arrival and departure times, and state should be registered by the PI containers and made available to the PI OI and thereby other relevant actors. Embedded smart sensors in PI containers, which are also part of this layer, are used for the purpose of retrieving this data.

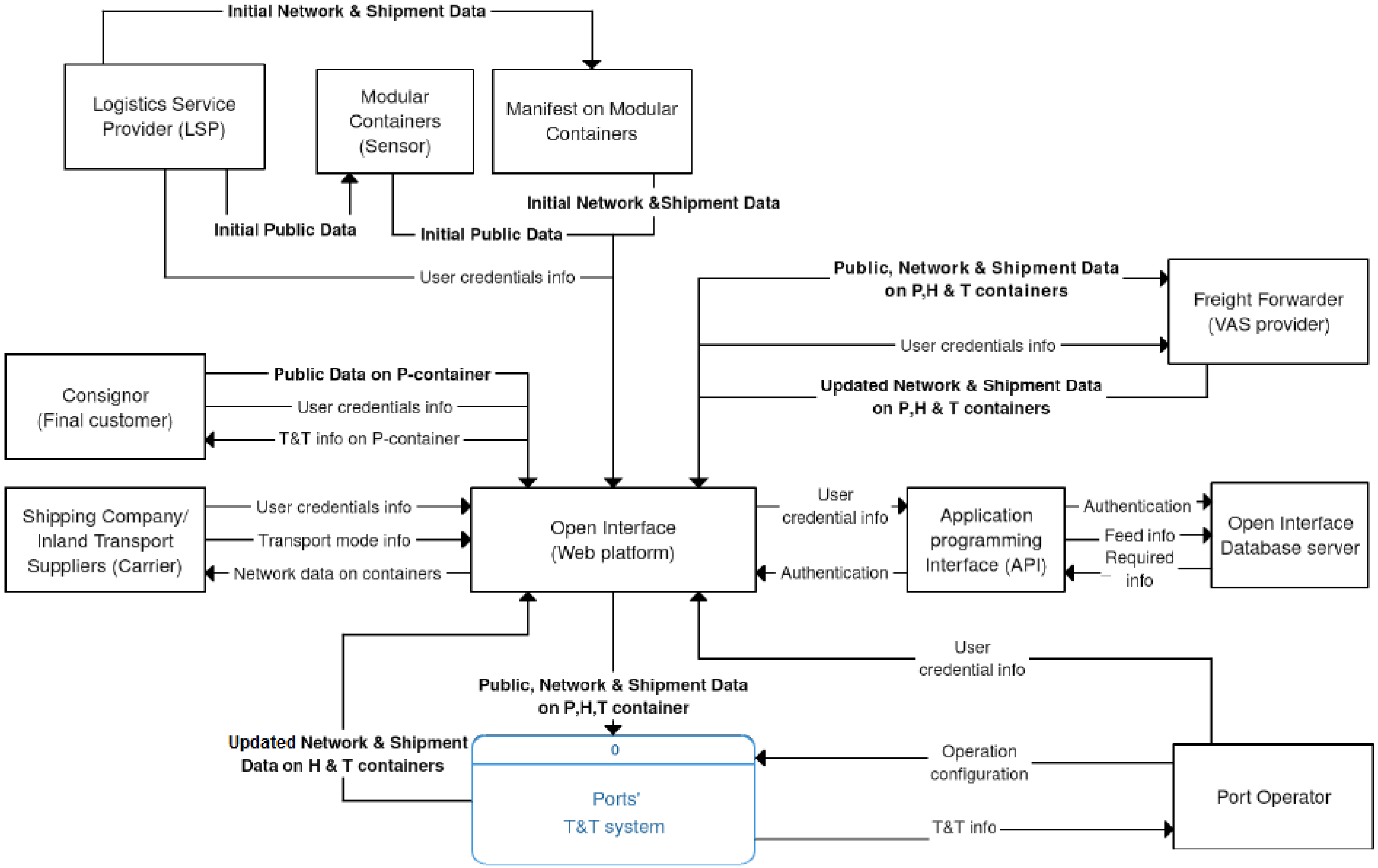

Figure 4.9: *Context diagram for the Information Layer of PI Ports' T&T Information Architecture*

4.6 Discussion

With respect to the overall approach, we positioned our research in the light of the four main elements of DSR in Section 4.3. We designed a new artefact in terms of an IA based on RAMI 4.0, which benefits the actors in the logistics chain, and satisfies the PI's requirements. We show that the use of RAMI 4.0 facilitates systematic reasoning and its applicability by means of the Teesport case. The IA presented in this paper highlights the organization, functions, interactivity of, and interaction between the information flows inside the port and with the PI OI. The main design limitations of the work are twofold. As the details of its implementation are not demonstrated yet in real life, the performance of the proposed IA cannot be validated and evaluated. However, the functional illustration of the IA in the Teesport case provides insights into the functioning of the IA in practice and its benefits for PI ports and its actors.

Another clear limitation of our design, although for justifiable reasons which are explained in Section 4.3, is the exclusion of the Communication and Integration layers.

From an operations perspective, Montreuil et al. (2018) pointed out that there are seven fundamental transformations from current into hyperconnected logistics city hubs in PI. We argue that our design supports the following three transformations that are of major importance to maritime PI ports: (1) becoming more agile through real-time dynamic and responsive shipping times; (2) becoming capable of conducting smart, real-time dynamic decisions on the container consolidation and internal flow orchestration; and (3) becoming active agents in the PI network, dynamically exchanging real-time information on the status of parcels, containers, vehicles, routes, and the other hubs. These major transformations are aimed at optimizing port operations to minimize vessel congestion times, and achieve of economies of scale, handling efficiencies, and enhanced security.

From an informational perspective, Sallez et al. (2016) listed identification, T&T, state monitoring, data compatibility and interoperability, and confidentiality as being essential in the PI. McFarlane et al. (2016) emphasizes that the value of T&T can be captured in accessibility, quality, and usefulness of information throughout the logistics chain, thus impacting the operational efficiency and strategic competencies of the supply chain and its multiple participating actors. Lind et al. (2020) introduced the concept of PortCDM which will benefit all actors in the maritime logistics chain by more efficient data distribution and usage. By implementing our proposed IA, the aforementioned value of T&T can be realized and a contribution to the realization of PortCDM can be made. In this sense, our design of the IA also extends the common data model of the Modulushca project to the PI containers by focusing on the Asset, Information, Functional and Business layers.

PCSs positively impact port community performance by connecting IT systems of each of its members and enabling communication (Calderinha et al., 2020). Although this also counts for our design, our IA represents the functional level of a port system, and is not a replacement for PCSs. Current PCSs do not track and trace on shipment level, while the proposed IA does, however. Furthermore, our design states the need for the PI OI to allow PI ports to exchange information with external actors in the logistics chain to increase visibility, both inside the port and throughout the logistics chain. Alternatively, PCSs could fulfil the role of "PI coordinator" as specified by Sallez et al. (2016), offering global information-based services for interoperability and coordination of shipments. Depending on its role in the PI, PCSs could also adopt the proposed IA and its functionalities. Clearly, there are many potential interactions between ports and PCSs in the PI.

When considering the OLI model, it must be kept in mind that, being a translation of the OSI, it addresses PI system protocols, while RAMI 4.0 focuses on the supporting ICT. We position the Business Layer as OLI's reflection in the IA by showing general business processes and operations of the PI. In addition, we note that the operations of the OLI's Physical Layer (L1), Link Layer (L2), and Network Layer (L3) will be conducted by the port's T&T system, since these layers deal with (1) operating and moving physical elements, (2) detection and correction of events from the physical layer by means of a digital twin, and (3) interconnectivity, integrity and interoperability within the network, respectively (Montreuil et al., 2012). Furthermore, the services of the Routing Layer (L4) and the Shipping Layer (L5) are essential to PI ports' T&T system and its respective IA since these monitor the PI containers' information as they flow across the network, define the shipment composition of PI containers, and decide on their routing.

4.7 Conclusions and future research

The problem addressed in this paper is that ports need to adapt their T&T systems if they want to become part of and play an essential role in the global PI network. Currently, ports only support T&T information at container level, while in the PI, the load units that encapsulate individual shipments, i.e. PI containers, including the surrounding modular load system, become relevant. Until now, there has been no design-oriented work to enable the functioning of port T&T systems for the PI. Our main contribution to research is the tractable and reproducible design of an IA for the T&T functionality of maritime ports in a PI context.

The IA design approach allows us to explore the potential of key PI elements for ports to cope with future challenges in the PI. The application of the RAMI 4.0 visualizes the logistics in PI ports, including the information flows regarding the required logistics entities, the activities and interactions in T&T systems and respective operational processes. By means of encapsulation and modularity, space utilization is enhanced by creating loading units through the three standardized levels (P, H, and T) of PI containers. The PI OI platform allows PI ports to manage various informational interactions between internal and external actors for purposes of optimizing operations, and additionally, increase visibility throughout the logistics chain on these loading units by linking the T&T system to external ISs. The used protocols in the IA improve the visibility in PI ports by proposing guidelines for PI ports and external actors. The Teesport case demonstrates the future capability of PI ports to decompose and (re-)compose their inbound shipments on the basis of the standardized levels of PI containers with appropriate information accessibility and improved visibility in port logistics.

As standardization and investments in global T&T systems are key prerequisites for a globally functioning PI, we recommend that future work explores IT aspects of logistics operations in more depth. In parallel with our design case, we also find that the PI may require diverse design models that, for consistency purposes, can be based on the same reference framework. These should be in line with practical situations to support logistics chain visibility needs in theory and practice.

New research could apply more extensive testing of the information flows and the architecture, along with the various PI logistics entities. Quantitative methods in combination with simulations on PI ports could be conducted to evaluate how the three PI components enhance space utilization, supply chain visibility, and service offering capabilities, compared to current T&T systems. In addition, the integration of the information flows within the designed architecture into external ISs, by means of for example PCSs, is also forms a potential future research subject. Another avenue for future research would be the general applicability of our design to other types of PI hubs, such as rail-, air-, and road hubs. Although in our design, we focused on specifically maritime PI ports, general applicability of our design is expected, with appropriate extensions and adaptations. Lastly, although we intentionally excluded the Communication and Integration layers in the design of the IA, a next step in the design could be to specify the exact technology (software and hardware) that best supports our design.

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5 Alignment of port policy to the context of the Physical Internet

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Abstract: The Physical Internet (PI) is a paradigm-changing and technology-driven vision, which is expected to significantly impact the development of the freight transport and logistics (FTL) system as we know it today. However, the development of the current FTL system towards the PI creates much uncertainty for its current stakeholders. Ports are one of those stakeholders that are expected to be profoundly affected by the developments towards the PI. The main objective of this paper is to provide ports with insights and recommendations on robust policy areas towards the PI. We conducted a scenario analysis, in combination with multi-criteria decision analysis (MCDA), to determine the importance of the port performance indicators in the different scenarios and the effectiveness of different policies in the different scenarios. The results show that the most significant, uncertain, and orthogonal factors are *technological development* and *institutional development*. In addition, we identified the following policy areas: *(1) Transport Infrastructure, (2) (PI) Standardization, (3) Advanced Terminal Areas, (4) ICT Hardware, (5) Information Systems & Platforms,* and *(6) Sustainability Management*. In the different scenarios, Information Systems & Platforms followed by (PI) Standardization are considered most effective. Transport Infrastructure is considered most relevant when technological and institutional developments are lagging and competitiveness rests more on physical access. The main implication of the research is that for a proper alignment with the PI vision, ports should prioritize the implementation of digital solutions, increasing supply chain interconnectivity and visibility. Furthermore, the research shows that standardization will be a necessary means to achieve a seamless flow of goods and information between stakeholders in the PI.

5.1 Introduction

Freight transport and logistics (FTL) contribute around 15% to the world's GDP and account for over 10% of a finished product's costs on average (Mervis, 2014). Simultaneously, among others, by transportation marking its presence with over 30% of the global carbon emissions (IEA, 2019), today's FTL system is often considered as non-sustainable from an economic, environmental, and societal perspective (Montreuil et al., 2013). Additionally, as demonstrated by regular disruptions with resulting shock-effects on international trade and manufacturing, the system suffers from vulnerabilities and lack of resilience (Dickens et al., 2021).

Besides being fundamental components of the FTL system, ports function as critical facilitators of international trade, through which they contribute to the economic development of countries and regions (Arvis et al., 2018). With 80% of the total merchandise trade being transported over sea, annual global maritime trade volumes have surpassed 10 billion tons (Hoffmann et al., 2018). Ports, nowadays, can be considered as complex dynamic organic systems within both national socio-economic-political and globalized economic systems (Nijdam & Van der Horst, 2017). Whereas ports' economic value creation and complexity increase over time (Lee & Lam, 2016), they need to continuously adapt to their external environment due to changing economic and trading patterns, new technologies, legislation, and port governance systems (Haraldson et al. 2021).

The Physical Internet (PI), a paradigm-changing and technology-driven vision, is expected to impact these current economic and trading patterns, technologies, legislation and governance systems. In June 2006, the term PI was introduced in the domain of transport and logistics on the cover of The Economist (Markillie, 2006). Later, in his seminal paper, Montreuil (2011: p. 71) positioned the PI as an all-encompassing vision "for the future of how physical objects are transported, handled, stored, supplied, realized, and used across the world". By analogy with the digital internet (DI) (Van Luik et al., 2020), the PI proposes physical shipments to be encapsulated into multi-level modular containers (Ballot et al., 2014), which autonomously find their way through an open hyperconnected network of logistics networks (Fahim et al., 2021a). More recently, Montreuil (2020: p.2) defined the PI as a "hyperconnected global logistics system enabling seamless open asset sharing and flow consolidation through standardized encapsulation, modularization, protocols and interfaces", where it aims to seamlessly connect physical, informational and financial flows (Treiblmaier, 2019). The development towards the PI is expected to have a profound impact on the functioning of today's FTL system. Although it has been recognized as a promising vision by both academia and industry, the development is uncertain for many current stakeholders in the FTL system, and requires (collaborative) research initiatives from academia, industry, and governmental institutions.

Ports are one of those stakeholders that are expected to be significantly affected by the developments towards the PI. Port authorities (PAs) are the organizations responsible for managing and developing a competitive, sustainable, and safe port environment (Dooms et al., 2013; Notteboom et al., 2013). PAs aim to synchronize the interests and actions of public stakeholders with the (sometimes divergent) behaviour, requirements, and strategic intent of private stakeholders, and their own strategic intent (Van der Lugt et al., 2013; Castelein et al., 2019). In developing its policies, the challenge for the PA is to balance its own strategic intent toward its different (categories of) stakeholders, while achieving a congruent value proposition for all its users (De Langen & Van der Lugt, 2017). Especially, since ports and their infrastructures are extremely asset heavy with high investment costs and needs (Parola et al., 2017), a thorough understanding of the way the FTL system develops is crucial to determine a correct allocation of investment resources and sustainable long-term policymaking for ports (Taneja et al., 2010). Failing to appropriately anticipate and act on these developments can result in negative consequences, not just for the port itself, but also for the local, national, and regional economy (Laird & Venables, 2017). The changes expected in the development of the FTL system towards the PI therefore are an important issue for port authorities to take note of and internalize to shape its policies. In this paper, we define port policy as a set of strategic activities and measures that enable long-term development, planning and learning to enhance overall port performance and attractiveness to its users (Bjerkan & Seter, 2019). As such, port policies encompass a selection of measures that should help to achieve strategic objectives and are robust for uncertainties in a future technological and institutional environment of ports. The optimal selection of measures will depend on the prevailing technological and institutional context.

A common practice to deal with uncertainty is scenario development (Von der Gracht & Darkow, 2010), while multi-criteria decision-analysis (MCDA) is one of the most recognized branches in theory about decision-making (Rezaei et al., 2014). Especially, in decision-making situations under uncertainty, a combination of scenario development and MCDA is expected to yield meaningful results. Earlier, Fahim et al. (2021a) constructed an evolutionary PI port development framework with potential future development paths, whereas Fahim et al. (2021b) analyzed intelligent agents' port performance evaluation and selection preferences in the context of the PI. The study which port policy fits best to the diverse possible contexts of the PI has so far been unexplored. The research question to be answered in this paper is as follows: "What are suitable policy areas for port authorities in the development towards the Physical Internet?"

With this study we aim to contribute to the literature on (1) maritime port policy and management in the technology-driven and paradigm-changing vision of the PI, and (2) policy selection in uncertain environments, through a combination of scenario development and MCDA.

The remainder of the paper is organized as follows. Section 5.2 provides a review of the relevant streams of literature for our research in the domains of the PI, future ports, and port policy. Section 5.3 presents the methodological approach. In Section 5.4, the construction of the contextual PI scenarios is described, and PI port performance indicators (PPIs) are presented. Section 5.5 presents the potential PI port policy areas. In Section 5.6, the aggregated results are presented and discussed with implications and recommendations for PAs. Section 5.7 ends the paper by means of a conclusion and recommendations for future research.

5.2 Literature review

5.2.1 PI consequences for networks

By positioning the PI as addressing the Global Logistics Sustainability Grand Challenge, the PI received much attention from academia, industry, and governmental institutions. In addition to the earlier provided definition, Montreuil (2020) defined eight PI Building Blocks for an open global FTL system: (1) unified set of standard modular logistics containers; (2) containerized logistics equipment and technology; (3) standard logistics protocols; (4) certified open logistics facilities and ways; (5) global logistics monitoring system; (6) open logistics decisional & transactional platforms; (7) smart data-driven analytics; and (8) certified open logistics service providers. Furthermore, although the PI can be still considered a relatively young vision, researchers have already applied many PI principles in research, using a range of different methods and tools. For a recent review of the PI research literature we refer to Pan et al. (2017) and Treiblmaier et al. (2020).

The above components have a large impact on transport networks. Dong & Franklin (2021) proposed a stylized network model for the PI network using the DI as a starting point, extending into a way that logistics metrics could be dynamically optimized. Based on the supply flows of the top 100 suppliers of two main retailers in France, by implementing PI principles in a simulation study, Ballot et al. (2012a) showed inspiring results of potential network cost savings, ranging from 4% to 26%, along with a potential threefold reduction in harmful emissions.

From a PI network node perspective, Ballot et al. (2012b), Meller et al. (2012), Montreuil et al. (2012), and Montreuil et al. (2021) addressed conceptual designs of intermodal hubs, road-based transit centers, road-based crossdocking hubs, and parcel logistics hubs, respectively. Focusing on ports, Fahim et al. (2021d) address the general management implications of the evolution of the PI for port and maritime practitioners. They identify the many influences of PI on the daily functioning of ports. Whereas Fahim et al. (2021b) construct an evolutionary PI port development framework to position these changes in time, Fahim et al. (2021a) analyze the changes that can be expected in intelligent agents' performance evaluation and selection preferences.

5.2.2 Future ports

Over centuries, ports have evolved from "simple" gateways between land and sea into highly complex multi-stakeholder customer-centric (intermodal) hubs for physical goods and information. Among others, the United Nations Conference on Trade and Development (UNCTAD, 1999), Flynn et al. (2011), and Lee & Lam (2016) constructed generational port development frameworks that describe this evolution of ports. In comparison with today, future ports will increasingly need to address the capability of real-time information sharing among its stakeholders, high-end technology-driven IT solutions, sustainability, physical and digital port connectivity, and value-added services (VAS) (Ha et al., 2019). Chu et al. (2018) claim that, since port operations can be regarded as structured, predictable, repetitive, and straightforward, the foundations of future ports lie in technology and automation, which, in combination with the use of (big) data and advanced analytics, have the potential of transforming ports into highly reliable and flexible FTL hubs. Furthermore, they stress the importance of digital solutions and real-time connectivity between port stakeholders. Moreover, future ports are expected to go further than connecting their own local communities, but rather reach beyond their boundaries on both land- and seaside, and eventually, become globally connected (Port of Rotterdam, 2020).

The evolutionary framework in Fahim et al. (2021b) describes the evolution from today's ports into globally hyperconnected ports in a fully functioning global PI, the PI Port Framework (PIPF). The PIPF shows that the main aspects, which influence the development of current ports into PI ports, can be captured in governance, operational, and digital dimensions. Also in the PI, Fahim et al. (2021a) identified costs, level of service, network interconnectivity, geographical location, reliability, and information systems (ISs) as most important indicators for port performance. Montreuil et al. (2018), however, stress that, to create a fully functioning PI, standardization of interfaces and protocols is a prerequisite. Ports need to develop digital capabilities which 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). In achieving the aforementioned, interconnected and interoperable ISs (of the different stakeholders), together with data and information (exchange) platforms, such as Port Community Systems (PCSs) (Moros-Daza et al., 2020), have a crucial role (Fahim et al., 2021c). PCSs are defined as neutral and open digital platforms, which enable secure exchange of information between both public and private stakeholders (IPCSA, 2015). PCSs aim to improve the competitiveness of port communities by automating, optimizing, and managing port and logistics processes through a single submission of data and connecting supply chains (IPCSA, 2018). Delenclos et al. (2018) argue that, to become a next generation port of the future, ports should aim for the implementation of the same technology-driven innovations that are disrupting other industries: connected ISs and platforms; cloud-based services; sensors and other Internet of Things (IoT) technologies; augmented reality; intelligent decision-making systems; blockchain; and big data analytics applications. Although up-front capital investments are high, port automation results in operational cost savings, while also contributing to performance enhancements and safety gains. S*uccessfully automated ports proved that operational costs could drop between 25 to 55 percent, and productivity could rise between 10 to 35 percent (Chu et al., 2018).* Montreuil et al. (2018) claim that, in order to exploit hyperconnectivity and modularity in the PI, hubs are required to: (1) receive and ship modular containers; (2) exploit pre-consolidation; (3) have less direct sources and destinations; (4) be ever more multi-actor and multi-modal service providers; (5) be more agile through real-time dynamic and responsive shipping times; (6) be capable of conducting smart, real-time dynamic decisions on the container consolidation and internal flow orchestration; and (7) be active agents in the PI network, dynamically exchanging real-time information on the status of parcels, containers, vehicles, routes, and the other hubs.

5.2.3 Port policy

From a policy perspective, Lam & Notteboom (2014) provide pricing, monitoring, market access control, and environmental standard regulation as four main categories for port policy, while Hou & Geerlings (2016) identify modal shift, technological means, and spatial measures as port policy options. Furthermore, whereas Kang & Kim (2017) refer to technologies, monitoring and upgrading, process and quality improvement, active participation, and communication and cooperation as main dimensions of port policy practices, Aregall et al. (2018) identified technology, dedicated infrastructure, monitoring program, engine regulations, regulatory instruments, intermodal service development, port dues and subsidy funds, certification, knowledge improvement, and concessions as main port policy measures. Bjerkan & Seter (2019) distinguish between concession agreements, collaboration, management of environment and energy, modal split, monitoring, port dues, and other managerial policies as main categories within port policy and management. O’Connor (2019) adds that a distinction can be made between investments in existing capabilities (e.g., hinterland accessibility, throughout capacity) and future capabilities (e.g., IoT technologies, intelligent decision-making systems) of ports.

Being the organizations that are responsible for the management and development of a competitive, sustainable, and safe port environment (Dooms et al., 2013; Notteboom et al., 2013), PAs need to make strategic decisions on investments within the geographical boundaries of the port area, but also beyond, in the fore- and hinterland. Simultaneously, PAs need to strategically position themselves among and towards both private and public port stakeholders (Van der Lugt et al., 2013; 2017) in an environment that is experiencing a process of (horizontal) collaboration (Senarak, 2020) and (vertical) integration (Zhu et al., 2019). The Port of Rotterdam (2019) authority states that, going forward, it will emphasize on developing its global hub function, industrial cluster, connections between the port, city and region, land and infrastructure, human capital, and innovation ecosystem. Aside from the PA, the main stakeholders that play a role in port and maritime operations are terminal operators, shippers, shipping lines, logistics service providers (LSPs), nautical service providers, (intermodal) transport companies, PCSs, customs authorities, and local, national and international governmental and regulatory bodies (Nijdam & Van der Horst, 2017).

5.2.4 Positioning of the work

Although over the past decade the number of publications, research areas and applied methods within the PI have been growing, the topic of maritime ports, while clearly relevant, has been underrepresented in the PI literature. Research that focuses on the way ports could design policy under the uncertain development of the FTL system towards the PI is still lacking. We aim to contribute to fill this void in the literature. By studying policy in a maritime port context and identifying intelligent agents' port performance preferences in different scenarios towards the PI, we contribute to the growing stream of PI literature. Additionally, by introducing the technology-driven and paradigm-changing vision of the PI in the context of port policy, we contribute to the port policy literature.

5.3 Methodology

5.3.1 Overall approach

The approach comprises a combination of *scenario development* and *MCDA*. We use scenario development to identify alternative and plausible futures in the PI context. We define an effective policy as one that maximizes a port's attractiveness for its potential users, by influencing port performance in the relevant dimension. Hence, policy effectiveness will depend on:

I. The relative importance of each port performance indicator to its users, and
II. The relative impact of port policy on each indicator.

Both these factors are highly context-dependent. Depending on the degree to which the PI has been realized, users may emphasize different performance criteria (for example, attach more importance to costs, or service quality) and it may therefore result in different dimensions of port performance becoming important. For example, when the PI is far advanced, investments in physical infrastructure may be less meaningful than in digital infrastructure. Our approach involves measuring I and II above separately and combining them into one policy effectiveness indicator. We measure relative importance of the *port performance indicators in each scenario* and the *impact of the policy areas on the port performance indicators in each scenario* using an MCDA method named best-worst method (Rezaei, 2015) . Using a weighted sum method then we can determine the *overall effectiveness of the policy areas in each scenario*, as follows.

$$E_{ps} = \sum_{i=1}^{n} w_{is} I_{pi} \qquad (1)$$

where

E_{ps} is the effectiveness of policy p in scenario s;

w_{is} is the relative importance (weight) of performance indicator i for overall port attractiveness in scenario s;

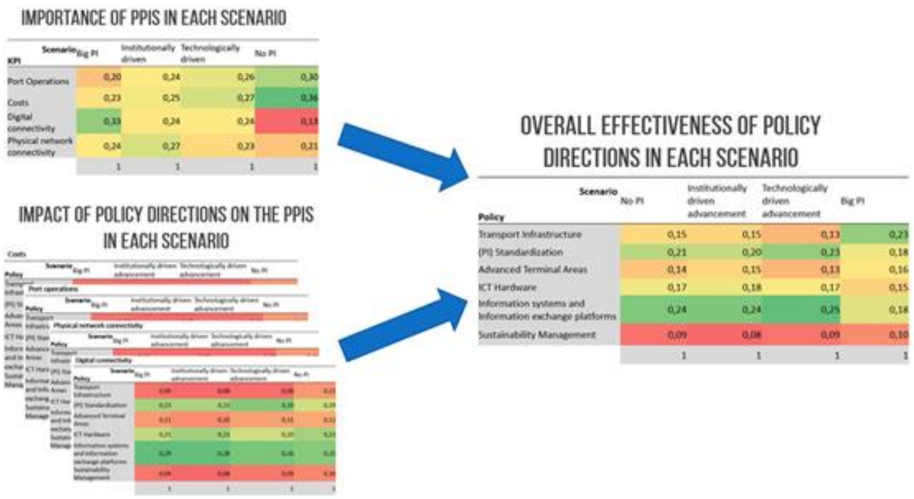
I_{pi} is the impact of policy p on indicator i.

Figure 5.1 illustrates how effectiveness of six policy areas is assessed for four PPIs under four scenarios. We elaborate on the detailed contents of these tables further on in the paper.

In the next sections, we subsequently discuss the scenario development and MCDA implementation approach.

5.3.2 Scenario development

In order to account for the uncertainty around the development of the PI, we formulate explorative scenarios using *scenario logic* (Enserink et al., 2010). The first step is to identify *contextual factors*. These are the variables that influence the development, performance and outcome of a particular system, and lie outside the influence of the *problem owner*. We derived contextual factors from a literature review. In the second step, the contextual factors are clustered into *driving forces*, which can be considered as the main underlying, independent variables influencing the contextual factors. In the third step, based on levels of *uncertainty* and *impact*, the most relevant driving forces are selected. By means of attributing opposing (positive/+ and negative/-) development directions to the driving forces, the scenario logic is constructed, and scenarios are obtained. Using this approach, the number of obtained scenarios is equal to 2 to the power of the number of selected driving forces. Balancing practicability and provision of meaningful results, we aim for a set of between three and eight scenarios (Bradfield et al., 2005). This is in line with previously conducted transport scenario studies (e.g., Tuominen et al., 2014; Melander, 2018; Port of Rotterdam, 2019; Inkinen et al., 2021).



IMPORTANCE OF PPIS IN EACH SCENARIO

KPI / Scenario	Big PI	Institutionally driven	Technologically driven	No PI
Port Operations	0,20	0,24	0,26	0,30
Costs	0,23	0,25	0,27	0,36
Digital connectivity	0,33	0,24	0,24	0,13
Physical network connectivity	0,24	0,27	0,23	0,21
	1	1	1	1

IMPACT OF POLICY DIRECTIONS ON THE PPIS IN EACH SCENARIO

OVERALL EFFECTIVENESS OF POLICY DIRECTIONS IN EACH SCENARIO

Policy / Scenario	No PI	Institutionally driven advancement	Technologically driven advancement	Big PI
Transport Infrastructure	0,15	0,15	0,13	0,23
(PI) Standardization	0,21	0,20	0,23	0,18
Advanced Terminal Areas	0,14	0,15	0,13	0,16
ICT Hardware	0,17	0,18	0,17	0,15
Information systems and Information exchange platforms	0,24	0,24	0,25	0,18
Sustainability Management	0,09	0,08	0,09	0,10
	1	1	1	1

Figure 5.1: *Evaluating the effectiveness of the six policies for 4 PPIs in 4 scenarios*

5.3.3 Multi-criteria decision analysis (MCDA) implementation

MCDA is a sub-field of operations research where multiple decision alternatives are analyzed with respect to multiple (often conflicting) decision criteria (Ishizaka & Siraj, 2018). Amongst several MCDA methods, we choose the Best Worst Method (BWM). It is a data-efficient method and has proven to produce consistent and reliable results (Rezaei, 2015). Through the initial selection of the best and worst criteria, to which the other criteria are compared, BWM is structured, easily executable, and time-efficient. By means of its pairwise comparisons, the BWM also helps decision-makers to gain additional valuable insights. Moreover, through the use of only integers, fundamental distance problems which might occur with the use of fractions in pairwise comparisons can be prevented (Rezaei, 2015). Finally, the use of two opposite references (best and worst) mitigates a potential anchoring bias of the respondent (Rezaei, 2020). For a more extensive review of BWM applications, we refer to Mi et al. (2019).

Our empirical research approach is built around the MCDA method and comprises four steps: (1) establishing criteria, (2) surveying experts, (3) determining weights, and (4) aggregating the results.

We used BWM for finding the weights of the *port performance indicators in each scenario* and the *impact of the policy areas on the port performance indicators in each scenario.* To avoid confusion we call the first implementation of BWM as BWM I and the second implementation BWM II.

Step 1 establishes a set of criteria. For BWM I, the PPIs represent the set of criteria. These are identified by means of literature review. For BWM II, the policy areas represent the set of criteria. To identify these policy areas, in addition to a literature review, we conduct a series of 14 semi-structured digital “face-to-face” expert interviews. We use a semi-structured interview approach to be able to give the interviewees some direction, while allowing them to freely express their opinions and complement the discussions. We select the fourteen experts on the basis of their experience with ports and/or PI, from academia and industry. Appendix 5.A provides a list of the 14 expert interviewees with respective functions and affiliations.

Step 2 obtains experts’ preferences as input data for the BWM. For the evaluation of the importance of the PPIs in the different scenarios in BWM I, a survey among 14 experts is conducted. For the evaluation of the effectiveness of the policy areas on the PPIs in the different scenarios in BWM II, a survey among 21 experts is conducted. In both cases, these experts are selected based on their academic experience with ports and/or PI, their (scientific) contributions to ports and/or PI, and/or industry experience. Appendix 5.B provides the lists of experts with respective functions and affiliations that participated in the surveys of BWM I and BWM II.

Step 3 determines the relative priorities/weights by means of the BWM. Since, in both BWM implementations, we are dealing with the preferences of a group of experts, we employ the Bayesian BWM. The Bayesian BWM is a probabilistic variant of BWM, which is specifically designed to obtain the relative priorities/weights of criteria for a group of DMs (Mohammadi & Rezaei, 2020a). Next to obtaining the relative priorities/weights, an additional valuable feature of the Bayesian BWM is that it provides ranking schemes. These ranking schemes are called credal rankings and are able to measure the degree to which a group of DMs prefers one criterion over another by means of a confidence level (Mohammadi & Rezaei, 2020b). The higher the confidence level, the more certain the group shows to be about a relationship between two criteria. Appendix 5.C provides a more elaborate explanation of the Bayesian BWM.

Step 4 uses a weighted sum method (see Eq. 1) to aggregate the weights of the *port performance indicators in each scenario* and the *impact of the policy areas on the port performance indicators in each scenario* which show the overall effectiveness of the policy areas in the different scenarios.

5.4 Results

In this section, following the four steps outlined above, we first describe the four scenarios that we obtained by scenario development. Secondly, we introduce the performance indicators and present their relative importance in the different scenarios. Thirdly, we present the identified policies that ports could use in their policy design and strategy formulation, as well as their effectiveness on performance indicators in the different scenarios. Fourthly, we present the aggregated results in terms of the overall effectiveness of the policy areas in each of the scenarios.

5.4.1 Scenarios

By means of a literature review, 27 external factors were identified that influence the global FTL system. Since we aim to incorporate all facets of the all-encompassing vision of the PI, and since both the technological and institutional components are crucial in the development towards the PI, we cluster the external factors into two aggregate forces: (1) *Technological development;* and (2) *Institutional development*. Appendix 5.D provides an overview of the 27 external factors with the corresponding driving forces.

For both driving forces, a positive and a negative future outcome is envisioned. In terms of technological development, a positive future outcome constitutes a *fast technological* *development*, whereas a negative future outcome constitutes a *slow technological development*. Similarly, in terms of institutional development, a positive future outcome constitutes a *progressive institutional development*, whereas a negative future outcome constitutes a *restrictive institutional development*. These potential positive and negative future outcomes are opposites on the two axes, which represent the driving forces of a scenario logic (see Figure 5.2), as prescribed by Enserink et al. (2010). By combining these potential positive and negative future outcomes of the two driving forces, four different scenarios towards the PI are created by means of the quadrants of the scenario logic.

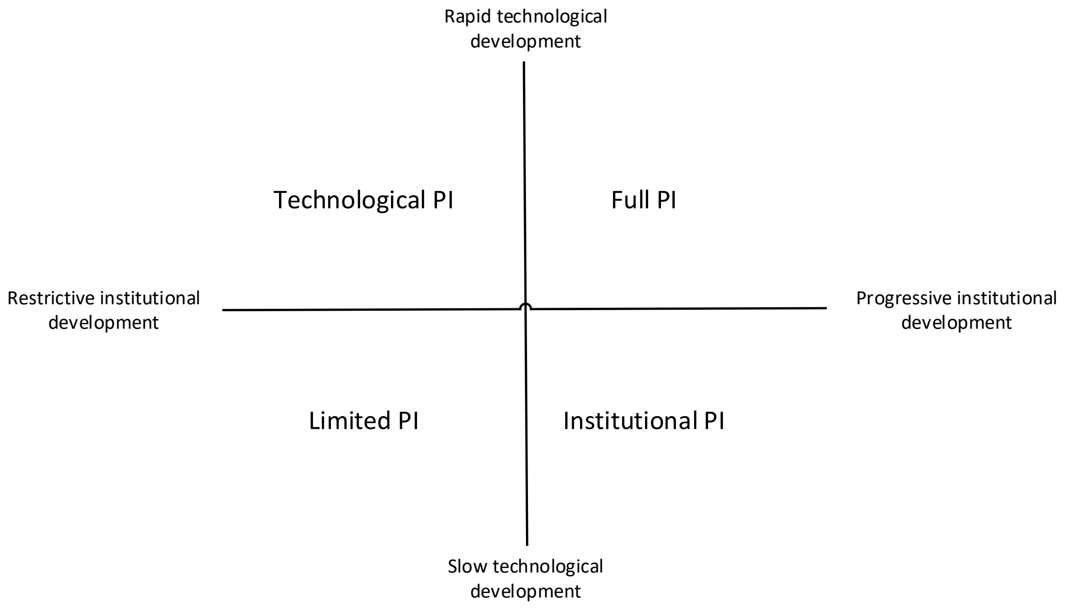


Figure 5.2: *Scenario logic for PI Ports*

Scenario 1: Limited PI

In the *Limited PI* scenario, due to slow technological developments, (implemented) solutions and applications in the fields of IoT, big data analytics and AI, and blockchain remain limited. Additionally, developments in cloud and edge computing (power) also lack behind, because of which both the autonomous real-time decision-making capabilities of intelligent agents, and the overall (hyper)connectivity between FTL stakeholders and entities do not come into fruition, as necessary for a well-functioning PI. Furthermore, from an institutional perspective, limited development in (PI) standards with a reluctance to collaborate and share resources by FTL stakeholders, partially, due to a lack in collaborative business models, and cohesive legal and regulatory frameworks, hinder the PI from moving forward. In this particular PI port scenario, the status quo of the FTL system remains and the PI will still be in its infancy by 2030.

Scenario 2: Institutional PI

In the *Institutional PI* scenario, the PI is driven by progressive institutional developments. Through the development and implementation of (PI) standards alongside the development and adoption of collaborative business models, and cohesive legal and regulatory frameworks, FTL stakeholders are willingly collaborating and sharing their physical and digital resources. Additionally, the modular PI containers are widely adopted in the FTL system. However, since technological developments are lagging behind with limitations, notably in the fields of IoT, big data analytics, AI, and blockchain, the PI operations are not being optimized. Additionally, developments in cloud and edge computing (power) also lag behind, because of which both the autonomous real-time decision-making capabilities of intelligent agents, and the overall (hyper)connectivity between FTL stakeholders and entities do not materialize. Hence, although the FTL stakeholders are collaborating, from a technological perspective, this scenario presents a similar FTL as we know today. A fully functioning PI is not yet to be expected by 2030.

Scenario 3: Technological PI

In the *Technological PI* scenario, technological development is fast and provides opportunities to implement the PI. Due to the wide adoption of technologies and applications related to IoT, big data analytics and AI, and blockchain, operations in the FTL system are being optimized. Additionally, developments in cloud and edge computing (power) are rapidly advancing, enabling autonomous real-time decision-making by intelligent agents and the overall (hyper)connectivity between FTL stakeholders and entities. However, due to lacking collaborative business models alongside legal and regulatory restrictions, FTL stakeholders still prove to be reluctant towards collaborating and sharing resources. Also, the development of (PI) standards is lagging behind. Hence, although technological innovations are being rapidly developed and implemented, through which the FTL system becomes smart and operations become more optimized and efficient, stakeholders are not fully hyperconnected and collaborating due to a lack in the adoption of (PI) standards and the willingness to share resources. In this scenario, a fully functioning PI is not yet to be expected by 2030.

Scenario 4: Full PI

In the *Full PI* scenario, rapid technological development is paired with progressive institutional development. The rapid technological development provides opportunities to implement the PI on a global scale. Implemented technologies and applications related to IoT, big data analytics and AI, and blockchain allow operations in the FTL system to be optimized. Additionally, developments in cloud and edge computing (power) are rapidly advancing, enabling intelligent agents to autonomously make real-time decision and the envisioned hyperconnectivity between FTL stakeholders and entities. Furthermore, through the development and implementation of (PI) standards alongside the development and adoption of collaborative business models, and cohesive legal and regulatory frameworks, FTL stakeholders are willingly collaborating and sharing their resources. Also, because of both technological and institutional advancement, modular PI containers and interoperable digital information platforms are widely adopted in the FTL system. In this particular scenario, a fully functioning PI is expected by 2030, through which the FTL system becomes more sustainable from an economic, environmental and societal perspective.

5.4.2 Port performance indicators (PPIs)

The analysis of port performance evaluation by its users has important implications for a port's policy formulation and investment decisions (Martinez Moya & Feo Valero, 2017). Whereas traditional port users, i.e., decision-makers, are represented by shippers, shipping lines, and logistics service providers, the routing protocol of the PI will require intelligent agents, i.e., intelligent containers and vessels, to support or replace current port users as decision-makers. Although port performance evaluation in a contemporary context has been abundantly investigated (e.g., Arvis et al., 2018; Ha et al., 2019; Rezaei et al., 2019), only Fahim et al. (2021a) addressed this topic in the advanced context of the PI. Hence, the indicators, which we use in this research to evaluate intelligent agents' port performance preferences in the different PI port scenarios, are inspired by Fahim et al. (2021a). Table 5.1 tabulates these PPIs with respective descriptions.

After having obtained the preferences of the group of 14 experts by means of a survey), we employed the Bayesian BWM to compute the relative importance of the indicators in the different scenarios as well as the respective credal rankings. Table 5.2 presents the relative importance of the performance indicators in the different scenarios.

Table 5.1: *Port Performance Indicators with respective descriptions*

Port Performance Indicator	**Description**
A. Port operations (PO)	Refers to the overall quality and efficiency of operations regarding container and vessel handling within the port boundaries. This includes factors such as speed, reliability, agility, flexibility, responsiveness, safety, security, and sustainability.
B. Costs	Refers to the costs from the perspective of the port users. These costs include transshipment costs and seaport duties.
C. Digital connectivity (DC)	Refers to the degree to which a port is digitally connected with its own community stakeholders and with other stakeholders of the FTL chain, in both fore- and hinterland.
D. Physical network connectivity (PNC)	Refers to the degree to which a port is physically connected with its fore- and hinterland. A higher degree of (intermodal) physical network connectivity leads to an increased degree in reliability, agility, flexibility, and responsiveness of the overall FTL chains in which a port takes part.

Table 5.2: *Importance of port performance indicators in the different scenarios*

Scenario **Port performance indicator**	**Limited PI**	**Institutional PI**	**Technological PI**	**Full PI**
Port Operations (PO)	0.301	0.240	0.259	0.204
Costs	0.365	0.251	0.275	0.231
Digital Connectivity (DC)	0.127	0.237	0.239	0.326
Physical Network Connectivity (PNC)	0.207	0.272	0.227	0.239
Sum	**1**	**1**	**1**	**1**

Costs and Port Operations are perceived as most important in the *Limited PI* scenario, which is in line with contemporary port performance evaluation and selection literature. Although the range of values in the importance of the PPIs in an *Institutional PI* scenario are relatively small, PNC and Costs are perceived as most important. This could be interpreted as the two PPIs that are least dependent on the technological development having the highest importance. However, at the same time, although the range of values in the importance of the PPIs also in a *Technological PI* scenario are relatively small, Costs and PO are perceived as most important. This could indicate that technology is mostly seen as a means for operational productivity and efficiency gains, while simultaneously decreasing costs of operations. DC and PNC are perceived as the most important PPIs in the *Full PI* scenario, which indicates that the PI is still mostly perceived as a digital innovation with achieving (hyper)connectivity in the FTL system as its main function. Between scenarios, the largest discrepancies can be found in the importance of DC between *Full PI* and *Limited PI* (0.326 - 0.127 = 0.199), and in the importance of Costs between the *Limited PI* and *Full PI* (0.365 - 0.231 = 0.134).

An additional observation is the discrepancy in the range of values (between the most and least important) of the PPIs in the different scenarios: 0.238 (0.365 - 0.127) in the *Limited PI* scenario; 0.035 (0.272 - 0.237) in the *Institutional PI* scenario; 0.048 (0.275 - 0.227) in the *Technological PI* scenario; and 0.122 (0.326 - 0.204) in the *Full PI* scenario. We can conclude that a larger range can be found in the more “extreme” scenarios, i.e., *Full PI* and *Limited PI*, while smaller ranges can be found in the “intermediate” scenarios, i.e., *Institutional PI* and *Technological PI*. Implying that, in the intermediate scenarios, the experts’ preferences in PPIs are more balanced, while, in the more extreme scenarios, the experts have a more distinguished preference.

The credal rankings are visualized in a weighted directed graph, where the nodes represent the importance and each link $s \overset{v}{\Rightarrow} s'$ indicates that indicator s is more important than indicator s' with confidence v. Figure 5.3 visualizes the weighted directed graph with respective credal rankings of the *Institutional PI* scenario, whereas Figure 5.4 visualizes the weighted directed graph with respective credal rankings of the *Technological PI* scenario. Although the guideline is that a confidence level of 0.50 can be used as a threshold value (Mohammadi & Rezaei, 2020a), values of 0.53, 0.58, 0.60, and 0.64 in Figure 5.3 indicate that there is some dissension between the experts’ opinions about those particular relationships. This also counts for the values of 0.59, 0.60, and 0.64 in Figure 5.4. The presence of some differences in the experts’ opinions is in line with the smaller range of values in the importance of the different indicators in the two intermediate scenarios. This also indicates that the experts are less confident on differentiating the relative importance of those criteria in these scenarios.

Most of the credal rankings of the *Limited PI* and *Full PI* scenarios are in full or almost full confidence levels, which is in line with the observation of the experts having a distinguished preference in importance of port performance indicators in the more “extreme” scenarios. Hence, the conclusion can be drawn that the importance differences of the PPIs in these two scenarios are determined with full or almost full confidence by the group of experts.

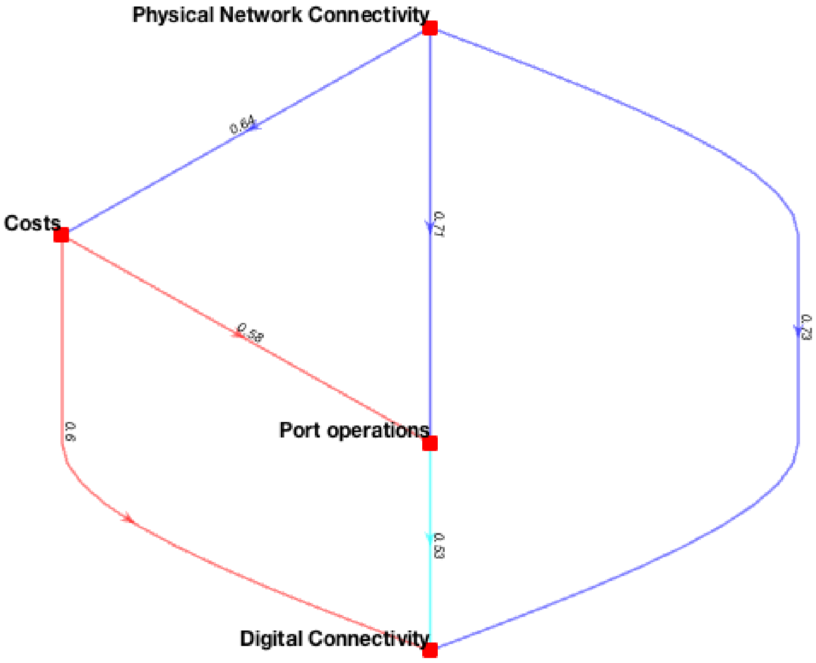


Figure 5.3: *Weighted directed graph with respective credal rankings of the Institutional PI scenario*

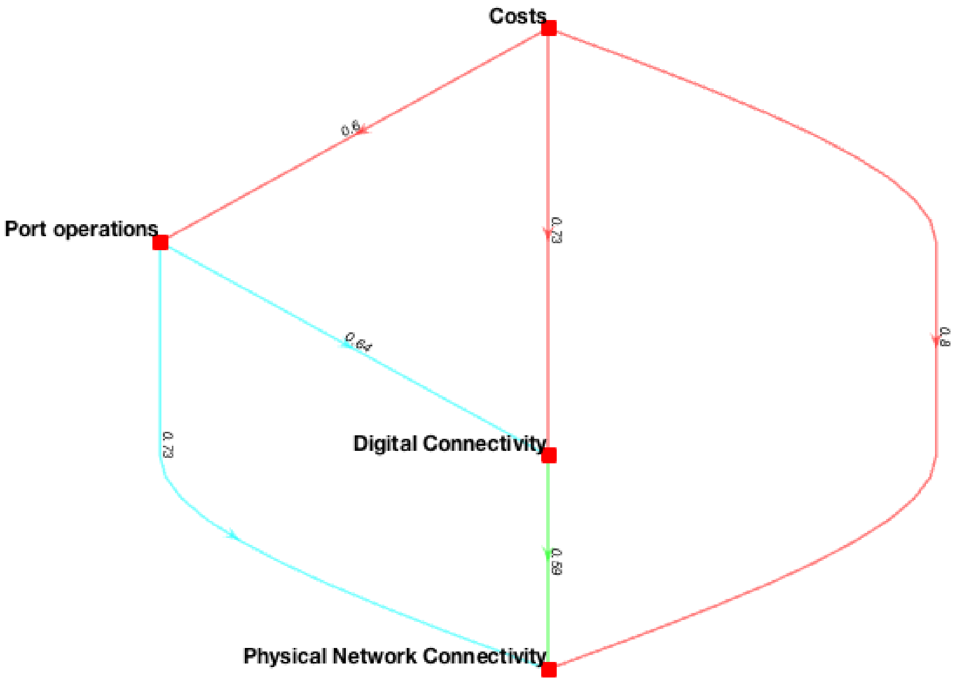


Figure 5.4: *Weighted directed graph with respective credal rankings of the Technological PI scenario*

5.4.3 Policies

Ports could implement several measures and invest in policies to maintain and improve their attractiveness for port users in the uncertain development towards the PI. To identify policy areas that ports could use in their policy design and strategy formulation, we conducted a literature review and a series of 14 semi-structured expert interviews. Although there are various ways to categorize policies (e.g., Lam & Notteboom, 2014; Hou & Geerlings, 2016; Kang & Kim, 2017; Aregall et al., 2018; Bjerkan & Seter, 2019), in this paper, we define six areas that bear particular relevance for ports developing towards the PI. The defined policy areas with respective descriptions are tabulated in Table 5.3.

After having obtained the preferences of a group of 21 experts by means of a survey, we employed the Bayesian BWM to compute the relative impact of the policy areas on each of the PPIs in the different scenarios as well as the respective credal rankings. Table 5.4 presents the impact of the policy areas on the PPIs in the different scenarios. However, since all the credal rankings were far above the threshold value of 0.5, which indicates that the difference of the impact of the policy areas in the different scenarios are determined by the group of experts with confidence, we decided not to show the weighted directed graphs.

It becomes evident that Information Systems and Platforms and (PI) Standardization are the most impactful policies on Port Operations and Costs in all scenarios, except in the Limited PI scenario where Transport Infrastructure is considered most impactful. Regarding Digital Connectivity, we can observe that, in addition to (PI) Standardization and Information Systems and Platforms, ICT Hardware is considered a significantly impactful policy area in all scenarios. With respect to Physical Network Connectivity, Table 5.4 indicates that Transport Infrastructure is the most impactful policy area in all scenarios, except in the Technological PI scenario where Information Systems and Platforms is considered the most impactful policy area. Another clear observation is that Sustainability Management is the least impactful policy area on all PPIs in all scenarios.

Table 5.3: *Policy areas with respective descriptions*

Policy area	**Description**
A: Transport Infrastructure (TI)	In improving a port's attractiveness, a PA could invest in the *transport infrastructure (TI)* to, among others, enhance the (multi-modal) accessibility of the port, both by land and sea, and increase its capacity (De Langen, 2008; Lee & Flynn, 2011; Montreuil et al., 2018). This includes investments, such as the enlargement of the rail shunting yard capacity and the deepening of the waterside access channel to ease draft restrictions so that larger vessels can berth (Notteboom 2016; Castelein et al., 2019). In the longer term, investments in offshore ports and Hyperloop terminals could also be desirable (DP World, 2020). Additionally, this policy area includes investments beyond the physical port boundaries in terms of developing the hinterland (distribution) infrastructure (De Langen, 2008; Rodrigue & Notteboom, 2010), inland- and dry terminals, extended gates, (adjacent and integrated) rail and Hyperloop terminals, and airports. The latter could be joint investments with other FTL stakeholders.
B: (PI) Standardization (PIS)	This policy area includes the development of standards, required for, for example, interoperable information systems (ISs), the digitalization of the Bill-of-Lading and customs declarations, nautical standards, physical and digital interfaces, protocols, and modular (PI) containers. PAs could contribute to setting these standards by coordinating with organizations, such as the World Trade Organization (WTO), International Maritime Organization (IMO), International Port Community Systems Association (IPCSA), Digital Container Shipping Association (DCSA), International Taskforce Port Call Optimization (ITPCO), and GS1, but also with other FTL stakeholders, such as shipping lines, LSPs, shippers, and customs authorities. Once particular standards are chosen and adopted, PAs could further stimulate their implementation and adoption by means of incentives and rules in concession agreements, access regulation, and pricing strategies (De Langen 2008; Lam & Notteboom 2014; Van der Lugt et al., 2017; Aregall et al. 2018; Notteboom & Lam 2018).
C: Advanced Terminal Areas (ATA)	For ports to be capable of conducting smart, real-time dynamic decisions on the container consolidation and internal flow orchestration (Montreuil et al., 2018), PAs could invest in the development of dedicated *advanced terminal areas (ATAs)*. Within these ATAs, the automated (Rodrigue & Notteboom., 2021), and later autonomous, (re)positioning and crossdocking of the PI containers could take place (Fahim et al., 2021b; 2021c). Once the PA developed an ATA, it could operate it itself or outsource the operations to a third party while keeping it within the port.
D: ICT Hardware (ICT-H)	Advanced *ICT Hardware (ICT-H)* in ports will be necessary to achieve the desired level of connectivity and visibility in the PI (Fahim et al., 2021c). Additionally, ICT-H, i.e., sensors and wireless communication technologies, enables fast- and fact-based

	exchange of information, which allows ports to become more agile, dynamic and responsive (Montreuil et al., 2018), and contributes to the efficiency and sustainability of port operations (Fernández et al. 2016; Botti et al. 2017; Douaioui et al. 2018; Molavi et al. 2020; Ahmad et al., 2021). ICT-H also enables IoT-, blockchain-, and Automatic Identification System (AIS) applications in ports (Belfkih et al., 2017; Rajabi et al., 2018; Yang et al. 2018; Hasan et al., 2020; Ahmad et al., 2021), which enhance the overall level of efficiency, connectivity, and visibility of port operations. The technological readiness of edge- and cloud computing plays a critical in the effectiveness of these decentralized systems (Wang & Sarkis, 2021).
E: Information Systems and Platforms (ISP)	For ports to be active multi-modal agents in the PI network, dynamically exchanging real-time information on the status of PI containers, vehicles, routes, and the other hubs (Montreuil et al., 2018), the PA has an important role in the development of interoperable *information systems and platforms (ISPs)*, such as a PCS. Additionally, to achieve the desired level of connectivity to facilitate seamless informational and financial flows, interoperable ISPs are a prerequisite. PAs are required to integrate their own ISs and stimulate the integration of ISs throughout the port community (and beyond), ensuring interoperability and exchangeability within the port community (and beyond) (Rodrigue, 2010). The PA could improve the smart functionalities of its ISs by applying AI, IoT and big data analytics (Belfkih et al. 2017; Yang et al. 2018; Hasan et al., 2020; Ahmad et al., 2021). Additionally, the PA could play a facilitating role by developing a neutral digital information platform (Ding, 2020; Kapkaeva et al, 2021), i.e., PCS (Moros-Daza et al., 2020), to provide "single version of the truth" informational services, required for an efficient, transparent, and cost effective coordination of shipments by multiple stakeholders. Furthermore, these ISPs could be connected with the fore- and hinterland to digitally integrate ports within a global PI.
F: Sustainability Management (SM)	Negative externalities, resulting from port operations and related activities, have been given more attention in recent years, favoring a holistic integration of sustainability (Ashrafi et al., 2020). *Sustainability management (SM)* is the policy area that aims to address the negative externalities. PAs can take measures to comply with, among others, environmental regulation and working conditions, while also developing monitoring systems to maintain safety, air quality, water quality, and control nuisances (Lam & Notteboom 2014; Di Vaio & Varriale 2018; Tseng & Pilcher, 2019). SM is also important for the port-city relations (Wiegmans & Louw, 2011). Additionally, emergent digitalization and information technologies are expected to bring opportunities that positively impact the environmental supply chain sustainability (Sarkis et al., 2021). Furthermore, PAs can encourage other port stakeholders to prioritize sustainability, for example, by incentives and rules in the concessions, access regulation, and pricing strategies.

***Table 5.4:** Impact of policy areas on the PPIs in the different scenarios*

Impact of policy areas on Port Operations (PO) in the different scenarios

Scenario **Policy area**	**Limited PI**	**Institutional PI**	**Technological PI**	**Full PI**
Transport Infrastructure	0.202	0.126	0.110	0.130
(PI) Standardization	0.173	0.214	0.247	0.195
Advanced Terminal Areas	0.172	0.169	0.132	0.141
ICT Hardware	0.151	0.179	0.160	0.179
Information Systems and Platforms	0.188	0.219	0.253	0.255
Sustainability Management	0.115	0.094	0.098	0.100
Sum	**1**	**1**	**1**	**1**

Impact of policy areas on Costs in the different scenarios

Scenario **Policy area**	**Limited PI**	**Institutional PI**	**Technological PI**	**Full PI**
Transport Infrastructure	0.260	0.179	0.139	0.167
(PI) Standardization	0.182	0.175	0.190	0.222
Advanced Terminal Areas	0.163	0.165	0.139	0.134
ICT Hardware	0.131	0.158	0.178	0.164
Information Systems and Platforms	0.168	0.242	0.263	0.241
Sustainability Management	0.096	0.081	0.091	0.072
Sum	**1**	**1**	**1**	**1**

Impact of policy areas on Digital Connectivity (DC) in the different scenarios

Scenario **Policy area**	**Limited PI**	**Institutional PI**	**Technological PI**	**Full PI**
Transport Infrastructure	0.107	0.080	0.081	0.084
(PI) Standardization	0.194	0.226	0.257	0.228
Advanced Terminal Areas	0.117	0.099	0.112	0.108
ICT Hardware	0.230	0.232	0.197	0.207
Information Systems and Platforms	0.255	0.285	0.266	0.286
Sustainability Management	0.097	0.078	0.087	0.087
Sum	**1**	**1**	**1**	**1**

Impact of policy areas on Physical Network Connectivity (PNC) in the different scenarios

Scenario **Policy area**	**Limited PI**	**Institutional PI**	**Technological PI**	**Full PI**
Transport Infrastructure	0.271	0.214	0.204	0.260
(PI) Standardization	0.154	0.190	0.211	0.166
Advanced Terminal Areas	0.176	0.175	0.141	0.196
ICT Hardware	0.131	0.141	0.135	0.132
Information Systems and Platforms	0.160	0.210	0.231	0.152
Sustainability Management	0.107	0.072	0.079	0.095
Sum	**1**	**1**	**1**	**1**

5.4.4 Aggregated results

The aggregated results, i.e., the overall effectiveness of the policy areas in each scenario, are obtained by combining the importance of the PPIs in each scenario with the impact of the policy areas on the PPIs in each scenario (See Eq. 1). These aggregated results are tabulated in Table 5.5.

Table 5.5: *Overall effectiveness of policy areas in the different scenarios*

Scenario **Policy area**	**Limited PI**	**Institutional PI**	**Technological PI**	**Full PI**
Transport Infrastructure	0.225	0.152	0.133	0.155
(PI) Standardization	0.175	0.201	0.226	0.205
Advanced Terminal Areas	0.163	0.153	0.131	0.141
ICT Hardware	0.150	0.175	0.167	0.174
Information Systems and Platforms	0.183	0.238	0.254	0.237
Sustainability Management	0.104	0.081	0.089	0.088
Sum	**1**	**1**	**1**	**1**

We observe that Information Systems and Platforms is the most effective policy, followed by (PI) Standardization. This counts for the Full PI scenario and the two intermediate scenarios, Institutional PI and Technological PI. In the Limited PI scenario, Transport Infrastructure is considered most effective. Advanced Terminal Areas and ICT Hardware are considered similarly effective in all scenarios, whereas Sustainability Management is considered least effective in all scenarios. With respect to Sustainability Management, it must be taken into account, however, that the effectiveness is evaluated against the PPIs (Port Operations, Costs, Digital Connectivity, and Physical Network Connectivity) from a user perspective.

5.5 Discussion

Reflecting on the importance of the port performance indicators in the different scenarios, we can observe that there is a highest-importance movement from the highest importance of Costs and Port Operations in the Limited PI scenario to Digital Connectivity and Physical Network Connectivity in the Full PI scenario. We consider this movement to be in line with typical contemporary port performance evaluation and selection literature (e.g., Rezaei et al., 2019), which prioritizes high quality logistics services against lowest costs, while also to be in line with the direction that the PI takes in literature (e.g., Montreuil et al., 2018), which is built around both digital and physical hyperconnectivity.

Reflecting on the overall effectiveness of the policy areas in the different scenarios, we can observe that, when moving further towards the Full PI scenario, Information System and Platforms becomes the most effective policy area, which can also be considered to be in line with literature on future ports (e.g. Chu et al., 2018; Delenclos et al., 2018; Ha et al., 2019) and ports in the PI (Fahim et al., 2021a; 2021c). Additionally, this observation can be considered to be in line with the development of a 6th generation of ports, succeeding the 5th generation of ports as described by Lee & Lam (2016). Among others, the importance of Information System and Platforms in the PI is underlined by Montreuil et al. (2018) by stating that ports are to be active agents in the multi-actor multi-modal PI network, dynamically exchanging real-time information on the status of parcels, containers, vehicles, routes, and the other hubs. Additionally, the significant effectiveness of (PI) Standardization can be found to be in line with expectations since standardization (of protocols and interfaces) has been described one of the essential cornerstones to realize a fully functioning PI (Montreuil et al., 2018). The low effectiveness of Sustainability Management can be considered a logical consequence of not having sustainability included as one of the port performance indicators. Hence, although sustainability within freight transport and logistics and green ports have received much attention and importance in literature, as long as port users do not value sustainability and the environment as they value the other port performance indicators in practice, the question remains whether port authorities will be willing to focus and significantly invest in the Sustainability Management policy area as well.

A fundamental challenge of increasingly complex multi-stakeholder networks to overcome is the matter of trust, transparency, and interoperability. Also for the functioning of the PI, requirements concerning visibility, hyperconnectivity, and trust need to be met. Blockchain is a technology that might have the potential to remove or at least alleviate some of these concerns in the context of the PI (Hasan et al., 2020). Additionally, neutral Information Systems and Platforms, such as PCSs, could play a facilitating role here. However, aside from the technical complexities, stakeholders' willingness to share (access to) resources, both digital (e.g. data) and physical (e.g. containers, vehicles, storages), will be a key determinant for the functioning of the PI, which could become one of its main impediments (Gunes et al., 2021). Port authorities can play a role here by acting as pioneers with the goal to create network effects, convincing other stakeholders to follow suit.

Another major technical challenge is the development and adoption of intelligent infrastructure, such as sensors, wireless communication technologies, and data centres (Molavi et al., 2020). Part of the challenge here lies in the cloud and edge computing power capabilities, safety and security, i.e. cybersecurity, and scale of implementation (Rajabi et al., 2018; Wang & Sarkis, 2021). Collaborative pilot projects and trials are seen as the way forward. Port authorities, again, can play a role here by acting as pioneers with the goal to create network effects, convincing other stakeholders to follow suit.

Lastly, although (PI) Standardization has been identified as one of the most effective policy areas, it does not bring much benefit if only a single stakeholder or entity adopts a particular solution or standard, regardless whether it is digital, physical, or procedural. The development and adoption of (PI) Standardization goes hand in hand with the development and adoption of innovative business and cooperative models, and legal and regulatory frameworks (Treiblmaier, 2020). However, since standards are a prerequisite for a functioning PI, also here, collaborative efforts by port authorities need to be undertaken and coordinated with organizations, such as World Trade Organization (WTO), International Maritime Organization (IMO), International PCS Association (IPCSA), Digital Container Shipping Association (DCSA), International Taskforce Port Call Optimization (ITPCO), and GS1, but also with other freight transport and logistics stakeholders and governing bodies.

When considering the implications of the effectiveness of the policy areas for ports altogether, it must be kept in mind that ports are still very dissimilar (Bichou & Gray, 2004; Delenclos et al., 2018). Hence, although we provide general policy areas that are applicable to ports, more detailed and specific measures could follow from more specific case studies.

5.6 Conclusions and future research

The main objective of this paper is to provide ports with insights and recommendations on robust policy areas towards the PI, given its highly uncertain development. Therefore, the main research question that was formulated in the beginning of this paper is: *What are suitable policy areas for port authorities in the development towards the Physical Internet?* With this paper, we aim to contribute to the literature on (1) maritime port policy and management in the technology-driven and paradigm-changing vision of the PI, and (2) policy selection in uncertain environments, through a combination of scenario development and MCDA.

Our main findings include the following. The most significant, uncertain, and orthogonal factors to consider in mapping potential futures for the development of the freight transport and logistics system into the PI are *technological development* and *institutional development*. In addition, we found that, moving into the PI, the connectivity indicators, *Digital Connectivity* and *Physical Network Connectivity*, become more important, while *Costs* and *Port Operations* become less important for port users. Furthermore, we identified the following policy areas for ports: *(1) Transport Infrastructure, (2) (PI) Standardization, (3) Advanced Terminal Areas, (4) ICT Hardware, (5) Information Systems & Platforms,* and *(6) Sustainability Management*. Here, we found that, moving into the PI, Information Systems & Platforms followed by (PI) Standardization are considered most effective.

The implications of the research are that ports should prioritize the development and implementation of digital (IT) solutions and systems that increase productivity and decrease costs of operations, while simultaneously increase supply chain interconnectivity and visibility. In addition, the research shows that standardization will be a necessary means to achieve seamless flow of goods and information between networks and stakeholders in the future context of the PI.

As avenues for future research, we propose the following. As our current policy areas were still formulated at a rather high level; we recommend to further operationalize them and assess them in more detail, to support their implementation. Additionally, adding a timeline to these measures could help policymakers to create a (dynamic) policy roadmap with respective concrete measures. Furthermore, it is recommended to conduct a cost-benefit analysis to assess the cost-effectiveness of the policy areas. Also, other quantitative analyses could be conducted to gain more insights into the impact of the policy areas, i.e., modelling what the effects of the policy areas are on quantitative indicators, such as container throughput, emissions, and revenue, in the different scenarios. The latter could be done using quantitative freight models and simulations. Lastly, since we mainly used European interviewees and survey respondents, we recommend research around the general applicability of our findings in other major parts of the world.

Appendix 5.A: List of expert interviewees

Table 5.A: *Expert interviewees*

Function	**Affiliation**
Full Professor	Delft University of Technology
Full Professor	Erasmus University Rotterdam
Full Professor	Georgia Institute of Technology
Innovation Manager	Groningen Seaports
Full Professor	Kedge Business School
Full Professor	Kuehne Logistics University
Full Professor	Mines Paris Tech
Innovation Manager	Port of Amsterdam
Innovation Manager	Port of Algeciras
Strategist	Port of Rotterdam
Innovation Director	Port of Valencia
Full Professor	University of Antwerp
Assistant Professor	University of Groningen
Full Professor	University of Groningen

Appendix 5.B: List of survey respondents

Table 5.B1: *Survey respondents BWM I*

Function	Affiliation
Associate Professor	Delft University of Technology
Full Professor	Delft University of Technology
Full Professor	Delft University of Technology
Researcher	Delft University of Technology
Innovation Manager	Groningen Seaports
Associate Professor	Kedge Business School
Full Professor	Kuehne Logistics University
Consultant	Maritime shipping consulting company
Innovation Manager	Port of Algeciras
Project Manager	Port of Hamburg
Strategist	Port of Rotterdam
Full Professor	University of Antwerp
Assistant Professor	University of Groningen
Full Professor	University of Groningen

Table 5.B2: *Survey respondents BWM II*

Function	Affiliation
Associate Professor	Delft University of Technology
Full Professor	Delft University of Technology
Full Professor	Delft University of Technology
Researcher	Delft University of Technology
Full Professor	Erasmus University Rotterdam
Full Professor	Erasmus University Rotterdam
Innovation Manager	Groningen Seaports
Consultant	Independent maritime shipping consultant
Associate Professor	Kedge Business School
Full Professor	Kuehne Logistics University
Consultant	Maritime shipping consulting company
Innovation Manager	Port of Algeciras
Innovation Manager	Port of Barcelona
Project Manager	Port of Hamburg
Strategist	Port of Rotterdam
Head of Strategy & Analytics	Port of Rotterdam
Innovation Director	Port of Valencia
Full Professor	University of Antwerp
Assistant Professor	University of Groningen
Full Professor	University of Groningen
Full Professor	University of Groningen

Appendix 5.C: Explanation of the Bayesian BWM

Assume that K experts evaluate n criteria $C = \{c_1, \dots, c_n\}$. To apply the Bayesian BWM, we should follow these 4 steps (Mohammadi & Rezaei, 2020a):

Step a: Expert k first selects the best (c_B^k) and the worst (c_W^k) criteria from C.
Every expert selects the best and the worst criteria from the set of earlier defined criteria. The best is considered the most important, whereas the worst criterion is considered the least important.
Step b: Expert k makes the pairwise comparison between the best criterion (c_B^k) and the other criteria.
Every expert expresses his/her preferences of the best criterion to the other criteria on a 9-point scale. Table C shows the scale numbers with respective linguistic variables of the 9-point scale. The pairwise comparison of expert k results in the "Best-to-Others" vector A_B^k as

$$A_B^k = (a_{B1}^k, a_{B2}^k, \dots, a_{Bn}^k), k = 1, 2, \dots, K, \tag{2}$$

where a_{Bj}^k represents the preference of the best criterion (c_B^k) over criterion $c_j \in C$ for expert k.

Table 5.C: *9-point scale with linguistic variables*

Scale number	Linguistic variable
1	Equally important
3	Moderately more important
5	Strongly more important
7	Very strongly more important
9	Extremely more important
2, 4, 6, 8	Intermediate values

Step c: Expert k makes the pairwise comparison between the worst criterion (c_W^k) and the other criteria. Here, every expert expresses his/her preferences of the other criteria over the worst criterion, again, on a 9-point scale. The pairwise comparison of expert k in step results in the "Others-to-Worst" vector A_W^k as

$$A_W^k = (a_{1W}^k, a_{2W}^k, \dots, a_{nW}^k)^T \tag{3}$$

where a_{jW}^k represents the preference of criterion $c_j \in C$ over the worst criterion for expert k (c_W^k).
Step d: Obtaining the aggregated weights $w^* = (w_1^*, w_2^*, \dots, w_n^*)$ and the weight for each expert $w^k, k = 1, \dots, K$ based on the following probabilistic model:

$$\begin{gathered}
A_B^k \mid w^k \sim \text{multinomial}(1/w^k), \forall k = 1, \dots, K, \\
A_W^k \mid w^k \sim \text{multinomial}(w^k), \forall k = 1, \dots, K, \\
w^k \mid w^* \sim \text{Dir}(\gamma \text{ x } w^*), \forall k = 1, \dots, K, \\
\gamma \sim \mathit{gamma}(0.1, 0.1), \\
w^* \sim \mathit{Dir}(1),
\end{gathered} \tag{4}$$

where *multinomial* is the multinomial distribution, *Dir* is the Dirichlet distribution and *gamma* (0.1, 0.1) is the gamma distribution with shape parameters of 0.1.
Considering that this model does not have a closed-form solution, Markov-chain Monte Carlo (MCMC) methods such as "just another Gibbs sampler" (JAGS) must be used (Mohammadi & Rezaei, 2020a). The useful outcome of the model is the posterior distribution of weights for every single expert and the aggregated w^*. However, the confidence of the superiority cannot be determined by solely comparing the weights. Therefore, in addition to providing the weights for every single expert and the aggregated w^*, the Bayesian BWM allows us to calibrate the degree to which one criterion is superior to another by means of a credal ranking.
Prior to providing a definition of the credal ranking, the credal ordering, which is the building block for the credal ranking, will be defined:

Definition 1 (credal ordering). For a pair of criteria c_i and c_j, the credal ordering O is defined as

$$O = \left(c_i, c_j, R, d\right)$$

where

- R is the relation between criteria c_i and c_j, i.e. <, >, or =;
- $d \in [0, 1]$ represents the confidences of the relation.

Definition 2 (credal ranking). For a set of criteria $C = (c_1, c_2, \ldots, c_n)$, the credal ranking is a set of credal orderings which includes all pairs $\left(c_i, c_j\right)$, for all $c_i, c_j \in C$.

The property of being able to assess the confidence of the superiority provides the DMs with more information that can significantly contribute to their decisions. It is considered even more important since we are dealing with group decision making (Mohammadi & Rezaei, 2020a). Another Bayesian test can now be devised to find the confidence of each credal ordering. The test is predicated on the posterior distribution w^*. The confidence that c_i being superior to c_j is computed as

$$P\left(c_i > c_j\right) = \int I_{(w_i^* > w_j^*)} P(w^*) \tag{5}$$

where $P(w^*)$ is the posterior distribution of w^* and I is 1 if the condition in the subscript holds, and 0 otherwise. This integration can be approximated by the samples via the MCMC. Having Q samples from the posterior distribution, the confidence can be computed as

$$P\left(c_i > c_j\right) \frac{1}{Q} \sum_{q=1}^{Q} I(w_i^{q*} > w_j^{q*})$$

$$P\left(c_j > c_i\right) \frac{1}{Q} \sum_{q=1}^{Q} I(w_j^{q*} > w_i^{q*}) \tag{6}$$

where w^{q*} is the q^{th} sample of $w^*$from the MCMC samples. Thus, for each pair of criteria, the confidence that one is superior over another can be computed. The credal ranking can be changed into a traditional ranking. Then, it is evident that $P\left(c_i > c_j\right) + P\left(c_j > c_i\right) = 1$. Hence, $c_i$is more important than c_j if, and only if, $P\left(c_i > c_j\right) > 0.5$ (Mohammadi & Rezaei, 2020b). As a result, the traditional ranking of criteria can be obtained by applying a threshold of 0.5 in the credal ranking.

Appendix 5.D: Driving forces with extermal factors

Table 5.D: *Driving forces with external factors*

Driving force	**External factor**	**Author(s)**
Technological development	Internet of Things (IoT)	Delenclos et al. (2018); Inkinen et al. (2021); Meindl et al. (2021)
	Artificial intelligence (AI)	Delenclos et al. (2018); Meindl et al. (2021); Wang & Sarkis (2021)
	Blockchain/distributed ledger technology	Treiblmaier (2019); Hasan et al. (2020); Ahmad et al. (2021); Wang & Sarkis (2021)

	(Big) Data analytics	Delenclos et al. (2018); Meindl et al. (2021); Wang & Sarkis (2021)
	Digitalization	Chu et al. (2018); Inkinen et al. (2021); Wang & Sarkis (2021)
	Digital information platforms	Delenclos et al. (2018); IPCSA (2018); Ding (2020); Fahim et al. (2021c); Wang & Sarkis (2021)
	Hyperloop	DP World (2020); Montreuil (2020)
	3D Printing	Inkinen et al. (2021); Meindl et al. (2021); Wang & Sarkis (2021)
	Robotics	DB Schenker (2021); Inkinen et al. (2021); Meindl et al. (2021)
	Drones	DB Schenker (2021); DHL (2021); Inkinen et al. (2021)
	Sensors	Delenclos et al. (2018); Inkinen et al. (2021); Meindl et al. (2021)
	Automation	Chu et al. (2018); Inkinen et al. (2021); Meindl et al. (2021)
	Cloud/Edge computing	Delenclos et al. (2018); Ding (2020); Meindl et al. (2021); Wang & Sarkis (2021)
	Intelligent systems	Delenclos et al. (2018); DB Schenker (2021); Inkinen et al. (2021); Meindl et al. (2021)
	5(/n)G network	Delenclos et al. (2018); Inkinen et al. (2021); Wang & Sarkis (2021)
Institutional development	Environmental regulations	Sarkis et al. (2021); DHL (2021); Fahim et al. (2021b); Inkinen et al. (2021)
	Global network integration	DHL (2021); Fahim et al. (2021b)
	Modularity/Containerization	Landschützer et al. (2015); Montreuil et al. (2016; 2018); DHL (2021)
	(Cyber)security	DHL (2021); Gunes et al. (2021); Inkinen et al. (2021)
	(PI) Standardization	Montreuil et al. (2018); Fahim et al. (2021a; 2021b; 2021c); Inkinen et al. (2021)
	(Collaborative) Business models	Treiblmaier et al. (2020); Inkinen et al. (2021); Meindl et al. (2021); Wang & Sarkis (2021)

	Labour protection	DHL (2021); Meindl et al. (2021)
	Trade agreements	Fahim et al. (2021b); Inkinen et al. (2021)
	Antitrust policies	Fahim et al. (2021b)
	Willingness to share (data and assets)	Ding (2020); Treiblmaier et al. (2020); DHL (2021); Gunes et al. (2021); Inkinen et al. (2021)
	Regulatory frameworks	Treiblmaier et al. (2020)
	Legal frameworks	Treiblmaier et al. (2020); Inkinen et al. (2021)

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6 The Physical Internet and maritime ports: Ready for the future?

Fahim, P.B.M., Rezaei, J., Jayaraman, R., Poulin, M., Montreuil, B., & Tavasszy, L. (2021). The Physical Internet & Maritime Ports: Ready for the Future? IEEE Engineering Management Review, 49(4), 136-149.

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 like 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 and platforms, and sustainability management.

6.1 The 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 non-sustainable. 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, a by the European Commission mandated logistics innovation platform, created an innovation roadmap for the PI, addressing key R&D challenges in dimensions like technology, organization, and governance (ALICE-ETP, 2020). As a global initiative, the annual International PI Conference (IPIC) is being 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 multi-level 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 6.1).

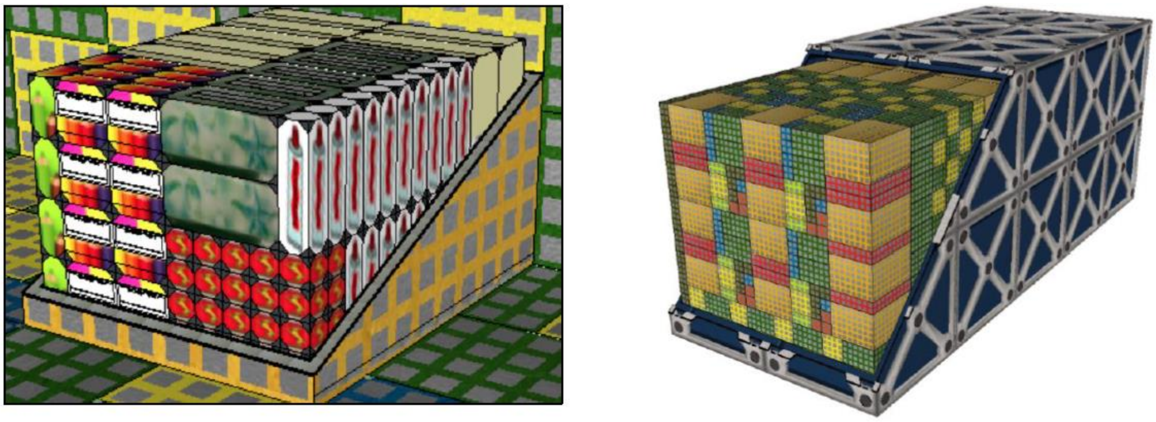

Figure 6.1: *Encapsulation of standardized containers at different levels inside the transport container (adopted from: Montreuil et al., 2016)*

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[1] See Van Luik et al. (2020); Dong & Franklin (2021); Kaup et al. (2021) for discussions on the DI/PI analogy

With 80% of total global trade being transported over 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 paper 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 towards 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?*

6.2 Maritime ports in the Physical Internet

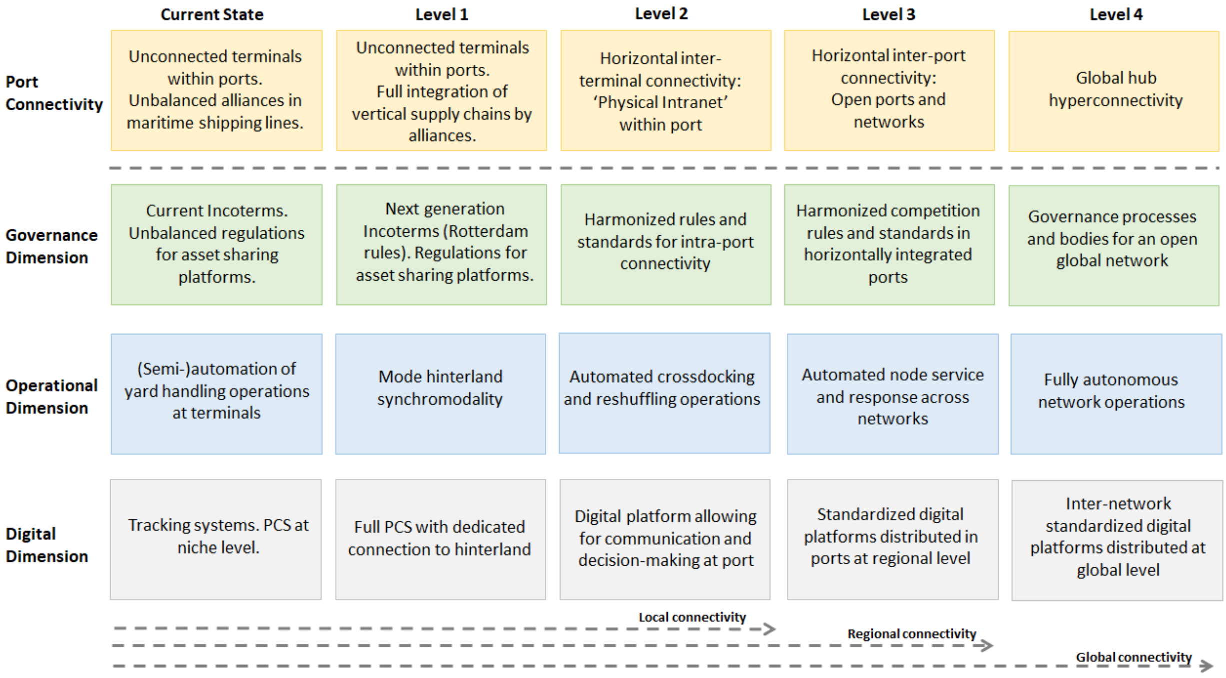
Maritime ports fulfil a critical role in the FTL system. Over centuries, ports have evolved from gateways between land and sea to customer-centric (intermodal) physical and informational hubs with a focus on serving its full community of stakeholders. Ports can be regarded as dynamic organic systems (Nijdam & Van der Horst, 2017), where both economic value creation and complexity increase over time (Lee & Lam, 2016), and play an important role in both national socio-economic-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 & 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 for 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 (VAS) (Ha et al., 2019). Moreover, tomorrow's ports will need to go beyond the scope of connecting the local community and reach into 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 sytem, which ports are a crucial part of. 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 depicted in Figure 6.2.

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. Firstly, 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. Secondly, port performance evaluation and selection is 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 & Franklin (2021) highlight *cost*, *time*, and *emissions* as important logistics performance metrics in the PI.



	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 6.2: *PI Port Framework (adopted from: Fahim et al., 2021a)*

Montreuil et al. (2018) claim that, for the PI to perform at the expected level, by supporting the envisioned hyperconnectivity, modularity, and network structure, logistics hubs are to: (1) receive and ship modular containers encapsulating parcel consolidated by next joint destination; (2) exploit pre-consolidation; (3) have less direct sources and destinations; (4) be ever more multi-stakeholder and multi-modal service providers; (5) be more agile through real-time dynamic and responsive shipping times; (6) be capable of conducting smart, real-time dynamic decisions on container consolidation and internal flow orchestration; and (7) 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 its 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 which 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 paper, we highlight and further elaborate upon these 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; and
4. Standardization of load units, interfaces, and protocols.

6.2.1 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 & Montreuil, 2016). All networks should, therefore, operate under the same standards, interfaces, and protocols. The network structure of the PI is required to have (1) a fast, cheap and reliable interconnection of nodes, transport modes and containers; (2) visibility on the (PI) containers (T&T); (3) secure and fair rewarding mechanisms for rendered services; and (4) integration of on-demand/per-use contracts for services (Meyer et al., 2019). In order to enable efficient and sustainable transport and logistics services, Montreuil et al. (2018) proposed a multi-plane hierarchical logistics network, interconnecting meshed networks along multiple planes. The system extends local, national, regional, and continental levels. See Figure 6.3 for an 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.

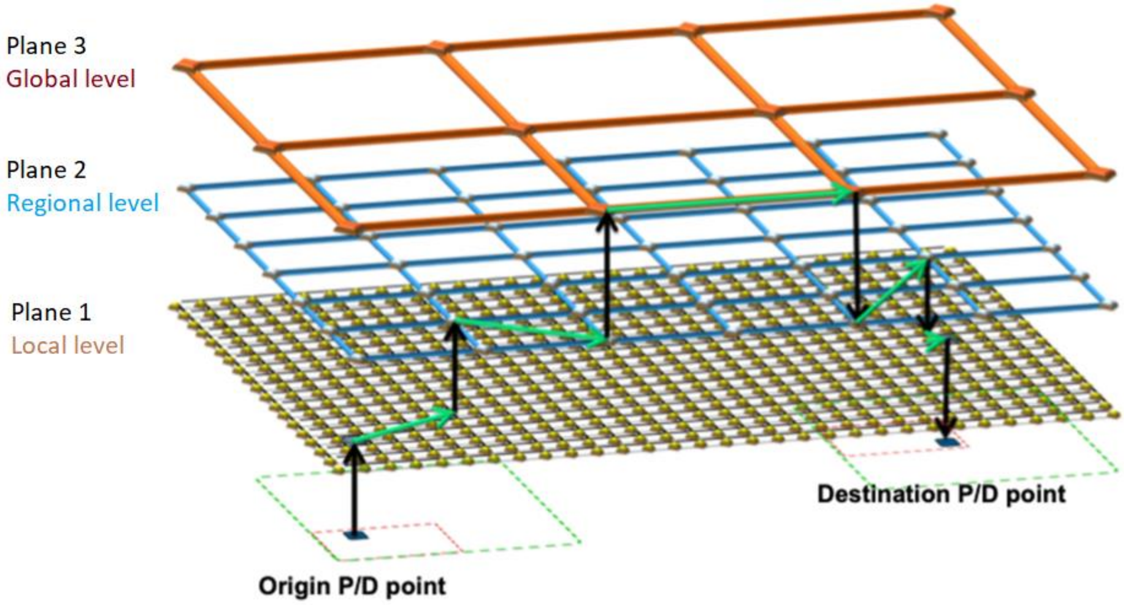


Figure 6.3: *Hierarchy in Physical Internet (PI) networks (adapted from: Montreuil et al., 2018)*

The multimodal meshing of networks creates many opportunities for re-routing 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 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 behaviour 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, like customs authorities, one can expect a strong increase in workload. Compared to today, besides the increase of 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.

6.2.2 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) argues 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 & Franklin (2021) and Fahim et al. (2021b) lean towards 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 & Van der Horst, 2017). The port authority 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 its 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 manoeuvring (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 secure exchange of data and information between public and private port stakeholders. Enhanced collaboration among these stakeholders leads to improved synchronisation, coordination and harmonisation 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 is 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 less options to differentiate, and increased difficulty to offer high service quality and visibility (Saxon, 2017). Figure 6.4 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, 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 predictability of events, sharing of 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 (SW) 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 its 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).

6.2.3 Digitzalization leading to visibility, automation, and intelligence

Digitalization has been recognized as a main enabler for ports and its 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, siloed operations) are significant, port automation results in operational cost savings, and contributes to performance enhancement and safety gains. *S*uccessfully automated ports show that operating expenses can drop between 25 to 55 percent and productivity can rise between 10 to 35 percent *(*Chu et al., 2018). Additionally, these investments could lead the way towards a new paradigm, 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).

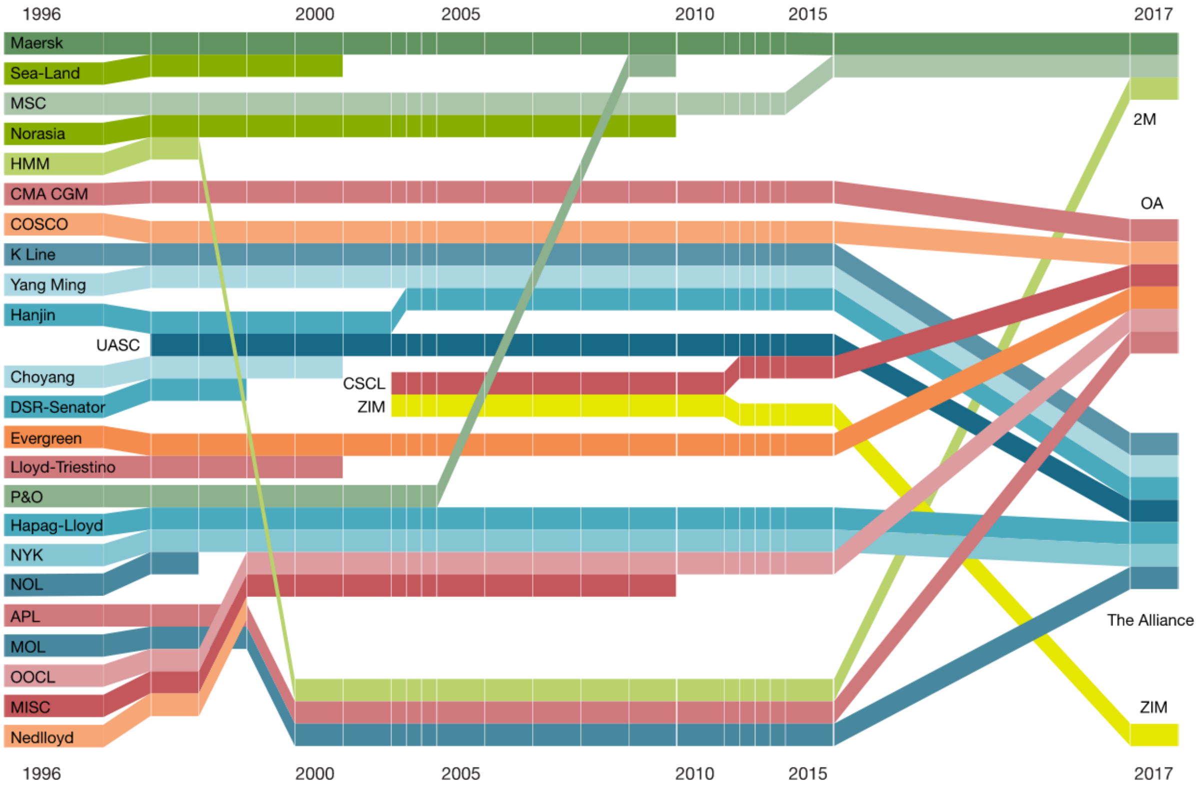


Figure 6.4: *Development of alliances over time (adopted from: Saxon, 2017)*

Recent developments in the area of distributed ledger technology such as blockchain represent a key enabler towards the realization of PI initiatives. For example, Galvez & Dallari (2018) propose 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 simultaneous change in all nodes, where all nodes possess the same exact copy of the ledger. In the current operational settings, most logistics and port operations systems are centralized making it 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 to 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 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) propose 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 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 are 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, scalability of transaction processing is a limiting factor to widespread adoption of blockchain-based solutions in port operations and logistics management.

6.2.4 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 40ft. sea containers). Firstly, 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. Figure 6.1 and Figure 6.5 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) mention 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 it to communicate real-time information with its 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 ports2.

Secondly, *smart interfaces* are essential in achieving system interoperability and hyperconnectivity. From an operational port perspective, this means that processes from marine

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

operations to crane movements to the control of yards and gates are seamlessly integrated (Chu et al., 2018), while 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).

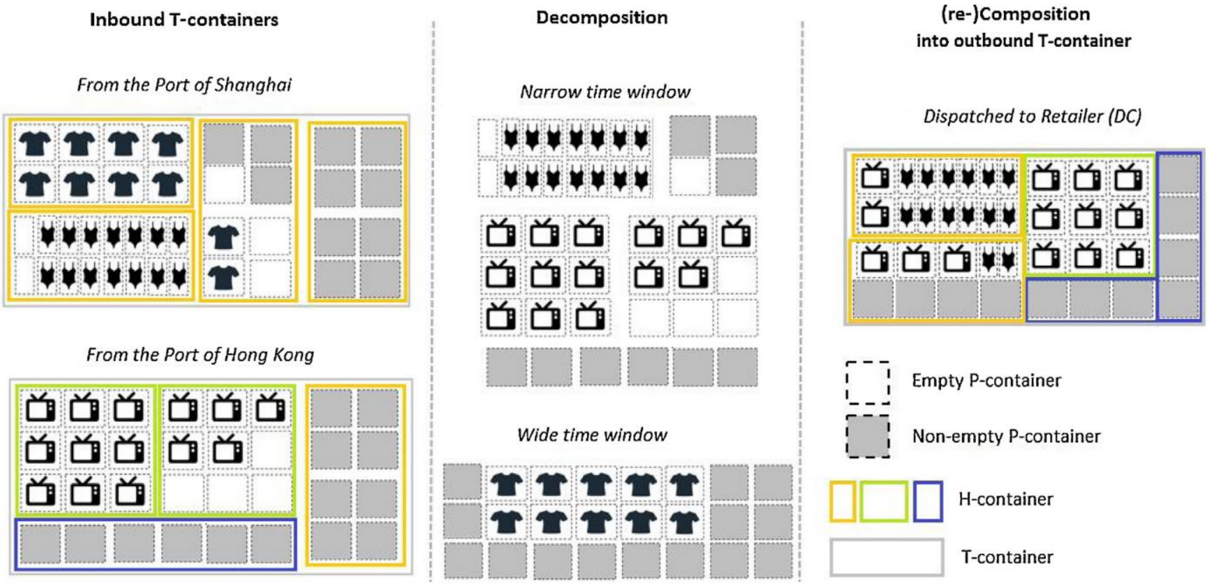

Figure 6.5: *Illustration of the Teesport use case for the repositioning operations of PI containers at a PI port (adopted from: Fahim et al., 2021c)*

Thirdly, 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 physical, digital, financial, human, and organizational means of the PI (Ballot et al., 2014).

6.3 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 ports towards the PI are discussed below.

6.3.1 Policy

Ports will need to anticipate on 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 & Gray, 2004), Fahim et al. (2021d) developed a set of generally applicable policy directions for ports towards the PI in six key areas, as shown below in Table 6.1.

Relating back 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 favour 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). In addition, ports, in coordination with other port community stakeholders, and governmental and regulatory bodies, such as the International Maritime Organization (IMO), the Digital Container Shipping Association (DCSA), 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 crossdocking 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 operational interfaces of PI entities (e.g. PI container, PI mover, PI conveyor) will play a crucial role. Ports, but also shipping lines, LSPs, shippers, and initiatives, such as the International Taskforce Port Call Optimization (ITPCO), 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 towards other stakeholders.

6.3.2 Challenges

One of the fundamental challenges of distributed and increasingly complex multi-stakeholder 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 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, storages), 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 in with the goal to convince other stakeholders to follow their suit, creating network effects.

Table 6.1: *Policy directions towards the PI*

Policy direction	**Description**
Transport Infrastructure	This policy direction includes investments in the port infrastructure, such as increasing its capacity, and investments on 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.

Another main challenge is the development and adoption of *intelligent infrastructure*, such as sensors, wireless communication technologies, and data centres (Molavi et al., 2020). Major challenges here lie in the processing power, safety and security, scale of implementation, and transparency (5GACIA, 2019). Testbeds 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 in with the goal 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 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 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).

6.3.3 Concluding remarks

Maritime ports currently do not possess substantive knowledge on how to anticipate on and contribute to the development of the PI. By means of this paper, we introduced the PI in a port and maritime context. In the beginning of the paper, 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 PI Port Framework (PIPF) shows that the evolution of maritime ports towards 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 its stakeholders and other ports. In the facilitation of this collaboration, the role of interconnected and interoperable information systems (IS) together with information platforms, such as Port Community Systems (PCSs), will be crucial. Furthermore, ports need to develop digital capabilities which provide intelligence, automation, and visibility, i.e. T&T, not only on container level but also on individual shipment level. Lastly, to create a fully functioning PI, standardization of load units, interfaces, and protocols is a prerequisite. As 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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7 Conclusions and recommendations

7.1 Introduction

The PI is an innovation that is expected to impact the current economic and trading patterns, technologies, legislation, and governance systems of the freight transport and logistics system. A paradigm-changing vision of this magnitude is expected to have a profound impact on all its actors. With 80% of the global trade being over sea, maritime ports are major actors that can be expected to be significantly affected by the developments towards the PI. Additionally, since ports are asset heavy and highly capital intensive, understanding the uncertainties in the development of the freight transport and logistics system is crucial for ports to determine appropriate strategies and allocate investments. Despite its potentially significant implications, the study of maritime ports in the context of the PI has remained underexplored. As a result, ports currently lack substantive knowledge on the way the global freight transport and logistics system will develop towards the PI, and the way ports could anticipate on and contribute to these developments. To help fill this gap, this research conceptually and empirically studies the future of maritime ports towards the PI.

In this final chapter, the main results of this thesis are discussed. The main findings from the five previous chapters are presented in relation to their respective research questions. Hereafter, the main recommendations for future research and policymakers are presented.

7.2 On the evolution of maritime ports towards the Physical Internet

RQ1: What are plausible development paths for the evolution of maritime ports towards the Physical Internet?

The purpose of the first study was to address the literature gap around the future of maritime ports towards the PI, uncovering plausible developments paths of maritime ports. By conducting a contextual scenario analysis, constructing a conceptual PI Port Framework, and executing a two-round Delphi study, a set of PI Port Development Paths that showed the potential evolution of ports towards the PI 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 Port Development Paths confirmed that the Governance dimension is most likely to become a bottleneck, and hence, the most critical in terms of port development. Secondly, the results from the Delphi study showed that an environment of high protectionism is expected to have a higher impact than a future with slow regulatory frameworks that could hinder market developments. Thirdly, under the most optimistic scenario, the PI in ports, as autonomous nodes in the freight transport and logistics system, is achieved on a regional (e.g. European) level at most. The ultimate stage of a globally functioning PI is not reached in any of the generated PI Port Development Paths. 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 port authorities and other logistics stakeholders have been made regarding governance-, operational-, and digital dimensions to increase the chances of reaching a globally functioning PI.

7.3 Port performance evaluation and selection in the Physical Internet

RQ2: How will port users in the Physical Internet evaluate port performance and select the most suitable port?

In the second study, we find a gap in the literature that identifies port performance evaluation and selection from the perspectives of intelligent containers and vessels, in the context relevant for the PI, i.e. one of dynamic routing of shipments and vehicles in a global network. We use insights from the port performance evaluation, port selection, and PI literature to study the combined problem.

Our main findings include that there are subtle differences between the container and vessel perspectives. Although the ranking of the highest level criteria is the same from both perspectives, there are significant differences in the importance of the underlying sub-criteria. In particular, (1) Transport Chain Quality is relatively more important for containers and Costs for vessels, (2) Level of Service, Network Interconnectivity, and Information Systems seem to become more important in the PI, compared to the current situation, and (3) the weighting of Costs differs per cost type (mostly Transshipment Costs for containers and Seaport Duties for vessels).

Overall, for port authorities, the general alignment of criteria and their weights between containers and vessels is reassuring, as they can largely manage one set of criteria to remain attractive for both. At the same time, some subtle differences have become apparent in this research, which allows them to be managed separately to some extent. Besides emphasizing on the different cost aspects for containers and vessels, a strong focus is needed on investments to become more agile, flexible, and responsive. Additionally, investments in information systems, i.e. digital connectivity and visibility, to be able to support real-time dynamic decision-making capabilities and enhanced collaboration in the PI, are necessary. Furthermore, to be competitive in the PI, port authorities should continuously improve their maritime and multi-modal hinterland connectivity.

7.4 An information architecture to enable track-and-trace capability in Physical Internet ports

RQ3: What is the proper arrangement of information flows on shipments and their characteristics, that supports T&T of goods inside a port, within the PI context?

The problem addressed in this chapter is that of ports' need to adapt their T&T systems to become part of and play an essential role in the global PI network. Currently, ports only support T&T information at container level. However, in the PI, the load units that encapsulate individual shipments, i.e. PI containers, become relevant. So far, design-oriented work to enable the functioning of port T&T systems for the PI has remained unaddressed. The main contribution of this chapter is the tractable and reproducible design of an information architecture (IA) for the T&T functionality of maritime ports in the context of the PI.

The IA design approach, used in this paper, allowed us to explore the potential of key PI elements for ports to cope with in the PI. The application of the Reference Architecture Model for Industry 4.0 (RAMI 4.0) visualizes the logistics in PI ports, including the information flows regarding the required logistics entities, the activities and interactions in T&T systems, and respective operational processes. By means of encapsulation and modularity, the fill rate is increased through the creation of load units, comprising three standardized levels (packaging, handling, and transport) of PI containers. The PI Open Interface platform allows PI ports to manage various informational interactions between internal and external actors for purposes of optimizing operations, and additionally, increasing visibility throughout the logistics chain. The protocols of the IA improve the visibility in PI ports and external actors. By means of the Teesport case, we demonstrate the future capability of PI ports to (re-)position their inbound shipments on the basis of the standardized levels of PI containers with appropriate information accessibility and improved visibility.

7.5 Alignment of port policy to the context of the Physical Internet

RQ4: What are suitable policy areas for port authorities in the development towards the Physical Internet?

Since ports and their infrastructures have extremely high investment costs and needs, when designing policies and allocating investment resources, a thorough understanding of the way the freight transport and logistics system develops is crucial. However, the development of the current freight transport and logistics system towards the PI creates much uncertainty. In this study, a combination of scenario analysis with MCDA is applied to determine the importance of the port performance indicators and the effectiveness of different policies in the different scenarios.

Our main findings include the following. Regarding the scenario analysis, the most significant, uncertain, and orthogonal factors to consider in mapping potential futures into the PI are *technological development* and *institutional development*. Also, we found that, moving towards the PI, from a port user perspective, the connectivity indicators (*Digital Connectivity* and *Physical Network Connectivity*) become more important, while *Costs* and *Port Operations* become less important. Additionally, we identified *(1) Transport Infrastructure, (2) (PI) Standardization, (3) Advanced Terminal Areas, (4) ICT Hardware, (5) Information Systems & Platforms,* and *(6) Sustainability Management* as most relevant policy areas for ports. We found that, moving towards the PI, Information Systems & Platforms followed by (PI) Standardization are considered most effective.

The research findings imply that ports should prioritize the development and implementation of digital (IT) solutions and systems that increase productivity and decrease costs of operations, while simultaneously increase supply chain interconnectivity and visibility. Furthermore, the study shows that standardization will be a necessary means to achieve seamless flow of goods and information between networks and stakeholders in the PI.

7.6 The Physical Internet and maritime ports: Ready for the future?

Q5: How can managers in the port and maritime industry anticipate on and contribute to the implementation of the PI?

Port managers currently do not possess substantive knowledge on how to anticipate on the development of the PI. By means of this chapter, we provide port and maritime sector practitioners with insights into the development of the freight transport and logistics system towards the PI, what this could mean for them, and the way in which they could contribute to its realization.

We argue that maritime port networks need to be redesigned as globally distributed, meshed, hierarchical, multimodal networks. Here, ports will need to intensively collaborate with its stakeholders and other ports. In the facilitation of this collaboration, the role of interconnected and interoperable information systems information (exchange) platforms 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. Lastly, to create a fully functioning PI, standardization of load units, interfaces and protocols is a prerequisite.

7.7 Recommendations for future research

Regarding the obtained development paths, we propose research into the estimation of future freight flows within each of the development paths by solving an alternative, PI-specific network design problem. This could enable further quantification of our results and could 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.

Regarding the port performance and evaluation study, we would like to recommend a regular re-evaluation of the (importance of the) criteria. As the PI can be considered to still be in its infancy, the changes it will bring to the freight transportation and logistics system will become more evident over time. This will bring more clarity to experts in the field as to which new port evaluation criteria might arise and the assessment of their respective importance. In that sense, this study serves as a basis for future studies as the PI comes closer to realization. Future research could also address the use of minimum threshold values, in terms of minimum scores of ports on evaluation criteria, as to become PI certified and allowed to participate in the PI network. This could be done in various ways, of which one would be by modelling maritime freight flows, while integrating the BWM model developed in this paper. The notion of a hierarchical network (local, regional, global) could also be integrated here. Furthermore, an even higher level of accuracy and consensus on the results could, for instance, be obtained by combining the BWM with a (multi-round) Delphi method. A last recommendation for future research on this topic is to study the general applicability of the developed BWM model and respective results to PI hubs in general, other than maritime ports.

As standardization and investments in global T&T systems are key prerequisites for a globally functioning PI, we recommend that future work explores IT aspects of logistics operations in more depth. In parallel with our design case, we also find that the PI may require diverse design models that, for consistency purposes, can be based on the same reference framework. These should be in line with practical situations to support logistics chain visibility needs in theory and practice. Furthermore, new research could apply more extensive testing of the information flows and the architecture, along with the various PI logistics entities. Quantitative methods in combination with simulations on PI ports could be conducted to evaluate how the PI components enhance space utilization, supply chain visibility, and service offering capabilities, compared to current T&T systems. In addition, the integration of the information flows within the designed architecture into external ISs, by means of for example PCSs, also forms a potential future research subject. Another avenue for future research would be the general applicability of our design to other types of PI hubs, such as rail-, air-, and road hubs. Although in our design, we focused on specifically maritime PI ports, general applicability of our design is expected, with appropriate extensions and adaptations, for example in the context of urban freight movements. Lastly, although we intentionally excluded the Communication and Integration layers in the design of the IA, a next step in the design could be to specify the exact technology (soft- and hardware) that best supports this design.

As our current policy areas were still formulated at a rather high level, we recommend to further operationalize them and assess them in more detail, to support their implementation. Additionally, adding a timeline to these measures, like used in our overall roadmaps, could help policymakers to create a dynamic and adaptive policy roadmap with respective concrete measures. Furthermore, it is recommended to conduct a cost-benefit analysis to assess the societal impact of the policy areas. Also, other quantitative analyses could be conducted to gain more insights into the impact of the policy areas, i.e., modelling what the effects of the policy areas are on quantitative indicators, such as container throughput, emissions, and revenue, in the different scenarios. The latter could be done using quantitative freight models and simulations. Since we mainly used European interviewees and survey respondents, we recommend research around the general applicability of our findings in other major parts of the world.

Last but not least, a major challenge and pressing innovation area for the future development of the PI lies in the system's governance, in terms of overall trust, and the development and adoption of universal standards, business and cooperative models, and legal and regulatory frameworks. Main disciplines to contribute here could be social and management sciences, using action research, case study research, and design science research to help establish promising new practices.

Summary

Freight transport and logistics (FTL) produce around 15% of the world's GDP and account for approximately 10% of finished product costs on average. However, through its contribution to the carbon footprint and traffic congestion, today's FTL operations are often considered to be non-sustainable from an economic, environmental, and societal perspective. Transportation marks its presence with over 30% of the global carbon emissions. Additionally, as demonstrated by regular disruptions and the resulting shock-effects on international trade and manufacturing, the global FTL system suffers from vulnerabilities and lack of resilience.

In addition to being critical components in the FTL system, maritime ports function as facilitators of international trade, through which they contribute to the economic development of countries and regions. Over centuries, maritime ports have evolved from simple gateways between land and sea into highly complex systems with a large and diverse number of stakeholders being involved, and various types of services being offered. This has caused maritime ports not only to function as (transshipment) hubs in FTL networks, but also a location where industrial and value-added services take place. In this way, ports can be considered as dynamic organic systems within both national socio-economic-political and globalized economic systems, where ports need to continuously adapt to their external environment by changing economic and trading patterns, new technologies, legislation, and port governance systems.

An innovation that is expected to impact the current economic and trading patterns, technologies, legislation, and governance systems, is the Physical Internet (PI). The PI is an all-encompassing vision for a future FTL system that transforms "the way physical objects are moved, stored, realized, supplied and used across the world", aiming towards greater economic, environmental, and societal efficiency and sustainability. By analogy with the digital internet (DI), physical shipments are encapsulated into multi-level modular containers and sent through an open hyperconnected network of logistics networks to their final destinations. The PI is defined as "a hyperconnected global logistics system enabling seamless open asset sharing and flow consolidation through standardized encapsulation, modularization, protocols and interfaces to improve the efficiency and sustainability of serving humanity's demand for physical objects".

A paradigm-changing vision of this magnitude is expected to have a profound impact on all actors of the FTL system. With 80% of the global trade being over sea, the maritime transport system can be expected to be significantly affected by the developments towards the PI. In addition, since ports are asset heavy and highly capital intensive, understanding uncertainties in the development of the FTL system is crucial for ports to determine appropriate strategies and allocate investments. Albeit recognized as a promising vision by both academia and industry with a growing interest and number of (scientific) publications, the development towards the

PI simultaneously creates much uncertainty for today's stakeholders of the FTL system and requires collaborative research initiatives by academic, industry, and governmental institutions. Nevertheless, the topic of maritime ports in the context of the PI so far has been unexplored. As a result, ports currently lack substantive knowledge on the way the global FTL system will develop towards the PI, and the way they could contribute to and anticipate on these developments.

The scientific contribution of this research is to conceptually and empirically explore the future of maritime ports towards the PI. We formulate the main research question as "*How can maritime ports anticipate on the developments towards the Physical Internet?*". Over the long-term, for the continuity of ports, it is important to gain insights into the possible consequences of a local, regional and global PI rollout, and to formulate robust strategies that will allow ports to secure a position as a strategic hub in a future PI network. We investigate this question from three key perspectives: scenarios for the development of the FTL system towards the PI (Chapter 2); requirements for ports to be attractive for its users in the PI (Chapter 3 & 4); and robust policy areas that answer to these scenarios and requirements (Chapter 5 & 6).

In Chapter 2, there are two main contributions. Firstly, we design an evolutionary port development framework that shows the evolution of a today's maritime port into a PI port. By identifying the main dimensions of the PI in relation to ports, the governance-, operational-, and digital dimension, this PI Port Framework shows how these dimensions evolve over time and result into local, regional, and global connectivity of ports. Secondly, by applying scenario analysis with a Delphi study among port experts, we develop an empirically supported picture of potential development paths for maritime ports in a PI context. 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.

In Chapter 3, we analyse port performance evaluation and selection from the perspective of intelligent agents in the maritime context of the PI. Here, we use insights from the port performance evaluation, port selection, and PI literature to study the combined problem. This is the first study that uses experts to help to assess probable changes in criteria and preferences of users in the FTL system in a PI context. Our objective is to define these criteria and explore their weighting in this new context. We propose two distinct autonomous decision-makers for port performance evaluation and selection in the PI: (1) intelligent containers and (2) intelligent vessels. We use the Bayesian Best-Worst Method (BWM) to derive weights for the criteria. We find that, compared to the current port performance evaluation and selection literature, in a first stage in the modelling of intelligent agents' performance preferences, subtle differences in weights mark the step from the present towards the PI. Partly, this is reassuring for port authorities as they can manage largely the same set of performance indicators to be attractive for both decision-makers. However, the results also show differences between agents, with an increased importance of, in particular, Level of Service, Network Interconnectivity, and Information Systems.

In Chapter 4, we contribute to literature by proposing an information architecture (IA) for maritime PI ports, which has been lacking so far. Differently than ports today, in the PI, decisions to split and bundle cargo across ships and other modes will not be made solely on the basis of long-term agreements by ports, but rather ever more dynamically and in real-time, aiming to reconsolidate shipments within the port area. This implies a need to reconsider the currently used information systems (ISs), and to gain understanding of future requirements to satisfy their needs. We exploit a design science research (DSR) approach to shape these requirements. Among the many components of future ISs, we study ports' track-and-trace (T&T) capability. The proposed IA enables to integrate T&T capability in PI ports by means of information carried on PI containers into the logistics chain via an open interface platform, which also supports interoperability among the various actors' ISs. The design is based on the

Reference Architecture Model for Industry 4.0 (RAMI 4.0). This model supports the analysis of PI ports in key dimensions along with hierarchical logistics entities, which could be used as a blueprint for IAs of PI ports, globally. We provide insights into the approach's applicability by means of the illustrative case of Teesport, located in Northeast England (United Kingdom).

Chapter 5 contributes to the port policy and PI literature by identifying suitable PI port policy areas that could help PAs to be attractive to port users towards and in the PI. Furthermore, a methodological contribution is made by combining scenarios for alternative futures with port performance dimensions in a novel multi-criteria, multi-futures port policy design framework. The results show that the most significant, uncertain, and orthogonal factors are technological development and institutional development. In addition, we identified the following policy areas: (1) Transport Infrastructure, (2) (PI) Standardization, (3) Advanced Terminal Areas, (4) ICT Hardware, (5) Information Systems & Platforms, and (6) Sustainability Management. In the different scenarios, Information Systems & Platforms followed by (PI) Standardization are considered most effective. Transport Infrastructure is considered most relevant when technological and institutional developments are lagging and competitiveness rests more on physical access. The main implication of this chapter is that for a proper alignment with the PI vision, ports should prioritize the implementation of digital solutions, increasing supply chain interconnectivity and visibility. Furthermore, this chapter shows that standardization will be a necessary means to achieve a seamless flow of goods and information between stakeholders in the PI.

Chapter 6 makes a contribution to the management literature, drawing together lessons towards the main research question. This chapter is focused on providing port and maritime practitioners with insights into the development of the FTL system towards the PI from a practical perspective, its implications in terms of opportunities and challenges, and the way they could anticipate on and contribute to its realization. We show that the PI, being a relatively young but compelling vision that envisions how many technological and organizational innovations could converge in a real-world FTL system, also addressing many existing cross-industry interests, such as standardization, digitalization, agility, resilience, and environmental sustainability. We 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 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.

Samenvatting

Goederenvervoer en logistiek (GVL) produceren ongeveer 15% van het wereldwijde BBP en nemen gemiddeld ongeveer 10% van de kosten van het eindproduct voor hun rekening. Door de bijdrage aan de CO_2-uitstoot en verkeerscongestie worden de huidige GVL-activiteiten echter vaak als niet-duurzaam beschouwd vanuit economisch, ecologisch en maatschappelijk perspectief. Transport heeft een aandeel van meer dan 30% in de wereldwijde CO_2-emissies. Bovendien, zoals blijkt uit regelmatige verstoringen en de daaruit voortvloeiende schokeffecten op de internationale handel en productie, lijdt het wereldwijde GVL-systeem onder kwetsbaarheden en een gebrek aan veerkracht.

Havens zijn niet alleen kritische componenten in het GVL-systeem, maar fungeren ook als facilitators van internationale handel, waarmee ze bijdragen aan de economische ontwikkeling van landen en regio's. Door de eeuwen heen zijn havens geëvolueerd van eenvoudige toegangspoorten tussen land en zee tot zeer complexe systemen, waarbij een groot en divers aantal belanghebbenden is betrokken en verschillende soorten diensten worden aangeboden. Hierdoor fungeren zeehavens niet alleen als (overslag)hubs in GVL-netwerken, maar ook als locatie waar industriële en value-added services plaatsvinden. Op deze manier kunnen havens worden beschouwd als dynamische organische systemen binnen zowel nationale sociaal-economisch-politieke als geglobaliseerde economische systemen, waar havens zich voortdurend moeten aanpassen aan hun externe omgeving door veranderende economische- en handelspatronen, nieuwe technologieën, wet- en regelgeving, en bestuurlijke functies en apparaten.

Een innovatie, die naar verwachting de huidige economische- en handelspatronen, technologieën, wet- en regelgeving en bestuurlijke functies en apparaten zal beïnvloeden, is het Fysieke Internet (FI). Het FI is een allesomvattende visie voor een toekomstig GVL-systeem dat "de manier waarop fysieke objecten worden verplaatst, opgeslagen, gerealiseerd, geleverd en gebruikt over de hele wereld" transformeert, gericht op grotere economische, ecologische en maatschappelijke efficiëntie en duurzaamheid. Naar analogie met het digitale internet (DI) worden fysieke zendingen ingekapseld in modulaire containers op verschillende niveaus en verzonden, via een open hyperverbonden netwerk van logistieke netwerken, naar hun eindbestemming. Het FI wordt gedefinieerd als een hyperverbonden wereldwijd logistiek systeem dat het naadloos verbinden van netwerken en delen van middelen om consolidatie van goederenstromen, wat mogelijk wordt gemaakt door middel van gestandaardiseerde inkapseling, modularisatie, protocollen en interfaces, om de efficiëntie en duurzaamheid van het GVL-systeem te verbeteren.

Een paradigmaveranderende visie van deze omvang zal naar verwachting een diepgaande impact hebben op alle actoren van het GVL-systeem. Aangezien 80% van de wereldhandel over zee gaat, is de verwachting dat het maritieme transportsysteem aanzienlijk zal worden beïnvloed door de ontwikkelingen in de richting van het FI. Omdat havens zeer kapitaalintensief zijn, is het bovendien van cruciaal belang voor havens om de onzekerheden in de ontwikkeling van het GVL-systeem te begrijpen om geschikte strategieën te bepalen en investeringen toe te wijzen. Hoewel erkend als een veelbelovende visie door zowel de academische wereld als de industrie met een groeiende belangstelling en een groeiend aantal (wetenschappelijke) publicaties, creëert de ontwikkeling naar het FI veel onzekerheid voor de huidige belanghebbenden van het GVL-systeem en zijn gezamenlijke onderzoeksinitiatieven van academische, industriële en overheidsinstellingen vereist. Desalniettemin is het onderwerp van havens in de context van het FI tot nu toe onontgonnen. Hierdoor ontbreekt het havens op dit moment aan inhoudelijke kennis over de wijze waarop het globale GVL-systeem zich zal ontwikkelen richting het FI, en de wijze waarop zij hieraan kunnen bijdragen en op kunnen anticiperen.

De wetenschappelijke bijdrage van dit onderzoek zit in het conceptueel en empirisch verkennen van de toekomst van havens richting het FI. De centrale onderzoeksvraag luidt “Hoe kunnen havens inspelen op de ontwikkelingen naar het Fysieke Internet?”. Op de lange termijn is het voor de continuïteit van havens belangrijk om inzicht te krijgen in de mogelijke gevolgen van een lokale, regionale en globale uitrol van het FI om robuuste strategieën te kunnen formuleren, waarmee havens een positie als strategisch knooppunt in een toekomstig FI-netwerk kunnen behouden en verwerven. We onderzoeken deze vraag vanuit drie belangrijke perspectieven: scenario's voor de ontwikkeling van het GVL-systeem richting het FI (Hoofdstuk 2); vereisten voor havens om aantrekkelijk te zijn voor gebruikers in het FI (Hoofdstuk 3 & 4); en robuuste beleidsterreinen die beantwoorden aan deze scenario's en eisen (Hoofdstuk 5 & 6).

In Hoofdstuk 2 zijn er twee belangrijke bijdragen. Ten eerste ontwerpen we een evolutionair raamwerk voor havenontwikkeling, dat de evolutie van een hedendaagse haven naar een FI-haven laat zien. Door de belangrijkste dimensies, de bestuurlijke-, operationele- en digitale dimensie, van het FI in relatie tot havens, te identificeren, laat dit het FI Havenraamwerk zien hoe deze dimensies in de loop van tijd evolueren en resulteren in lokale, regionale en wereldwijde connectiviteit van havens. Ten tweede, door scenarioanalyse toe te passen met een Delphi-studie onder havenexperts, ontwikkelen we een empirisch onderbouwd beeld van mogelijke ontwikkelingspaden voor havens in een FI-context. De resulterende verwachting is dat een volledig wereldwijd functioneren van het FI in 2040 mogelijk niet wordt bereikt. Ook laat onze analyse zien dat wereldwijde bestuurlijke functies en apparaten van GVL-systemen van cruciaal belang zijn voor het tempo van ontwikkeling en adoptie van het FI.

In Hoofdstuk 3 analyseren we hoe (de prestaties van) havens worden geëvalueerd en geselecteerd vanuit het perspectief van intelligente systemen in het FI. Hier gebruiken we inzichten uit de havenprestatie-, havenselectie- en FI-literatuur om het gecombineerde probleem te bestuderen. Dit is de eerste studie, welke experts gebruikt om te helpen bij het beoordelen van veranderingen in criteria en voorkeuren van gebruikers in het GVL-systeem in een FI-context. Ons doel in dit hoofdstuk is om deze criteria te definiëren en hun weging in deze nieuwe context te onderzoeken. We stellen twee verschillende autonome beslissers, die de evaluatie van havenprestaties en selectie van havens van in het FI: (1) intelligente containers en (2) intelligente schepen. We gebruiken de Bayesian Best-Worst Method (BWM) om gewichten voor de criteria af te leiden. Vergeleken met de huidige literatuur over evaluatie van havenprestaties en selectie van havens, vinden wij subtiele verschillen in de weging van de criteria. Gedeeltelijk is dit geruststellend voor havenbedrijven, aangezien zij grotendeels dezelfde prestatie-indicatoren kunnen beheren om aantrekkelijk te zijn voor de twee autonome beslisnemers. De resultaten laten echter ook verschillen zien tussen de twee beslisnemers, met een toenemend belang van met name Level of Service, Network Interconnectivity en Information Systems.

In Hoofdstuk 4 leveren we een bijdrage aan de literatuur door een informatiearchitectuur voor havens in een FI-context voor te stellen. Anders dan in de huidige situatie, zullen beslssing om vracht te splitsen en te bundelen in het FI niet alleen worden genomen op basis van langetermijnovereenkomsten van schepen en andere vervoerswijzen met havens, maar steeds dynamischer en in real-time. Dit impliceert de noodzaak om de momenteel gebruikte informatiesystemen te herbestuderen en inzicht te krijgen in toekomstige vereisten om aan de behoeften te voldoen. We gebruiken een design science research (DSR) methode om deze vereisten vorm te geven. Van de vele componenten van toekomstige informatiesystemen bestuderen we de track-and-trace (T&T) functie van havens. De voorgestelde informatiearchtitectuur maakt het mogelijk om T&T-mogelijkheden in FI-havens te integreren door middel van informatie die op FI-containers wordt vervoerd in de logistieke keten via een “open-interfaceplatform”, dat ook de interoperabiliteit tussen de informatiesystemen van de verschillende actoren ondersteunt. Het ontwerp is gebaseerd op het Reference Architecture Model for Industry 4.0 (RAMI 4.0). Dit model ondersteunt de analyse van FI-havens in belangrijke dimensies, samen met hiërarchische logistieke entiteiten, die kunnen worden gebruikt als een blauwdruk voor informatiearchitecturen van FI-havens, wereldwijd. We geven inzicht in de toepasbaarheid van de aanpak aan de hand van de illustratieve casus van Teesport, gevestigd in Noordoost-Engeland (Verenigd Koninkrijk).

Hoofdstuk 5 draagt bij aan het havenbeleid- en de FI-literatuur door geschikte FI-havenbeleidsterreinen te identificeren die havenbedrijvens kunnen helpen aantrekkelijk te zijn voor havengebruikers in het FI. Verder wordt een methodologische bijdrage geleverd door scenarioanalyse voor alternatieve toekomsten te combineren met havenprestatiedimensies in een nieuw multi-criteria multi-scenario’s ontwerpkader. De resultaten laten zien dat de meest significante, onzekere en orthogonale factoren technologische ontwikkeling en institutionele ontwikkeling zijn. Daarnaast hebben we de volgende beleidsterreinen geïdentificeerd: (1) Transportinfrastructuur, (2) (FI) Standaardisatie, (3) Geavanceerde Terminalgebieden, (4) ICT-hardware, (5) Informatiesystemen & Platforms en (6) Duurzaamheidsmanagement. In de verschillende scenario's worden Informatiesystemen & Platforms gevolgd door (PI) Standaardisatie als het meest effectief beleidsterren beschouwd. Transportinfrastructuur wordt het meest relevant geacht wanneer technologische en institutionele ontwikkelingen achterblijven en het concurrentievoordeel meer berust op fysieke toegang van de haven. De belangrijkste implicatie van dit hoofdstuk is dat havens voor een goede afstemming op de FI-visie prioriteit moeten geven aan de implementatie van digitale oplossingen, waardoor de interconnectiviteit en zichtbaarheid van de supply chain wordt vergroot. Verder laat dit hoofdstuk zien dat standaardisatie een noodzakelijk middel zal zijn om te komen tot een naadloze verbinding in goederenstromen en informatie tussen belanghebbenden in de FI.

Hoofdstuk 6 levert een bijdrage aan de managementliteratuur, waarbij lessen worden getrokken in de richting van de hoofdonderzoeksvraag. Dit hoofdstuk is erop gericht om haven- en maritieme professionals inzicht te geven in de ontwikkeling van het GVL-systeem richting het FI vanuit een praktisch perspectief, de implicaties ervan in termen van kansen en uitdagingen, en de manier waarop zij kunnen anticiperen op en bijdragen aan de realisatie ervan. We laten zien dat het FI, een relatief jonge maar boeiende visie die voorstelt hoe technologische en organisatorische innovaties zouden kunnen samenkomen in werkelijk GVL-systeem, ook inspeelt op veel bestaande sectoroverschrijdende belangen, zoals standaardisatie, digitalisering, veerkracht en ecologische duurzaamheid. We bouwen voort op de unieke positie van havens in het FI met de bijbehorende uitdagingen die zij met zich mee kan brengen. Tot slot bespreken we de vereisten waaraan havens moeten voldoen om hun rol in het FI op te kunnen nemen. We constateerden dat beleidsterreinen voor havens om bij te dragen aan de ontwikkeling en implementatie van het FI liggen op het gebied van transportinfrastructuur, (FI) standaardisatie, geavanceerde terminalgebieden, ICT-hardware, informatiesystemen en platforms en duurzaamheidsmanagement. De grootste uitdagingen en meest dringende innovatiegebieden voor de toekomstige ontwikkeling van het FI liggen in het algehele vertrouwen van belanghebbenden, en de interoperabiliteit van de verschillende systemen, de ontwikkeling en acceptatie van intelligente infrastructuur en universele normen, bedrijfs- en samenwerkingsmodellen en wet- en regelgeving.

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Patrick B.M. Fahim was born on the 27th of July 1987 in Munich, Germany. He obtained his BSc and MSc from the Delft University of Technology in Systems Engineering, Policy Analysis & Management. After obtaining his MSc degree in 2014, for several years, he worked in industry at one of the leading global logistics service providers. From 2017 to 2022, he was a Ph.D. Researcher at the Delft University of Technology. During this time, he was a Visiting Researcher at Fraunhofer IML (Germany), the Georgia Institute of Technology (USA), the Khalifa University (UAE), and the Abu Dhabi School of Management (UAE).

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