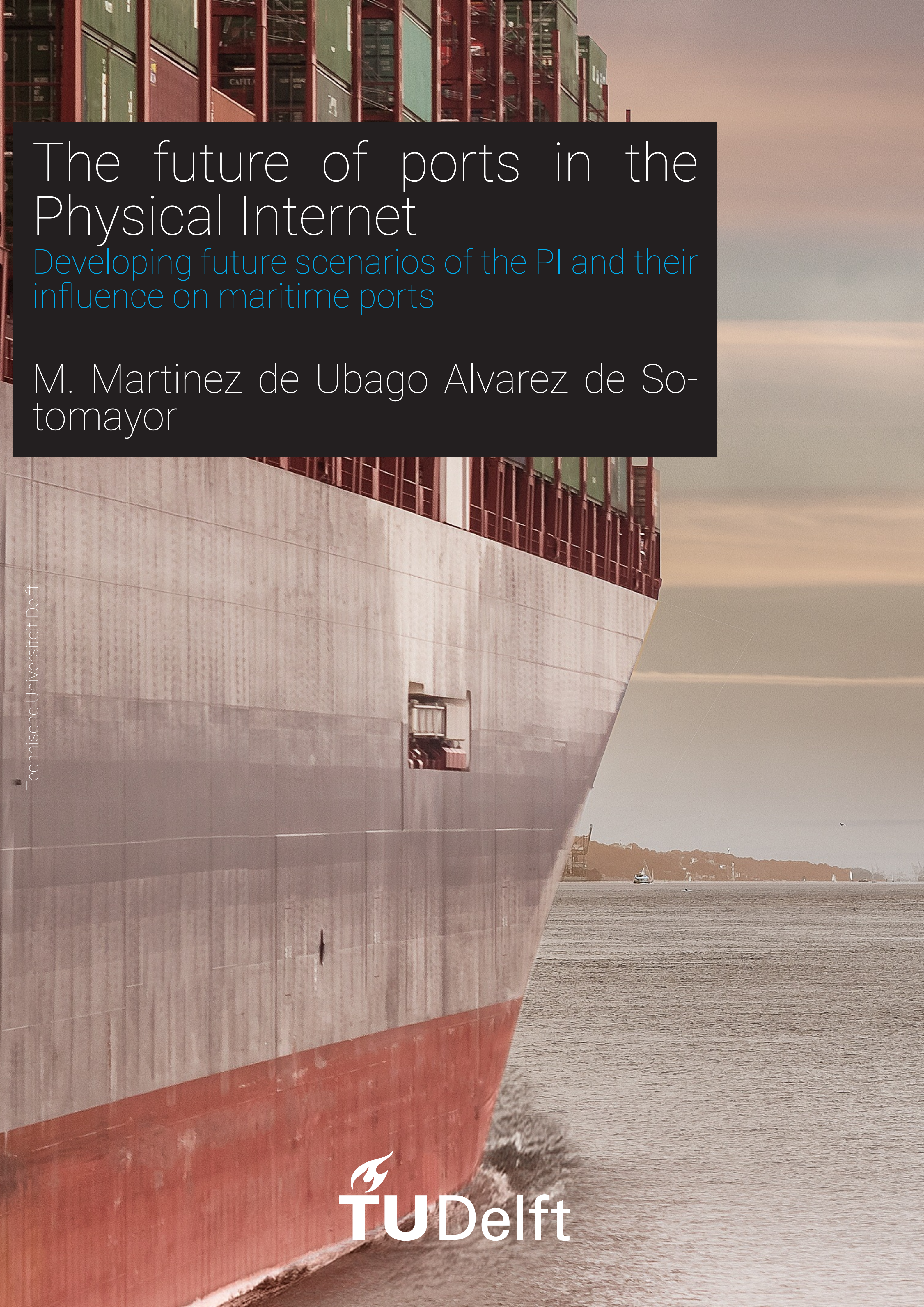

The future of ports in the Physical Internet

Developing future scenarios of the PI and their influence on maritime ports

M. Martinez de Ubago Alvarez de Sotomayor

Technische Universiteit Delft

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by

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It has not been easy to grasp a research that included countless hours of literature study, interviews with people that were geographically dispersed, and eventually bring in together vast knowledge in a topic were consensus is scarce. Yet I sincerely hope that the insights and results herein presented will help academics, industry or any other institution in their joint efforts towards the Physical Internet. Also in particular for the Port of Rotterdam, the most important maritime hub in Europe and avid collaborator in this thesis.

The first mention of this preface should go to Jeff Voster. With a similar research topic, we were both lost and struggling at the beginning of our theses, and therefore we had to work closely together. 'Eendracht maakt macht', which I believe it was the motto of the Republic of the Seven United Provinces of the Netherlands back in the late 1500s and 1600s, ironically makes a lot of sense here. For all those countless hours discussing ideas, drawing concepts with arrows that sometimes pointed nowhere, and great conversations we had in general both at University, and once in the car to Groningen, a massive thank you is the least I could say.

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To all of you, for your support, I sincerely thank you.

Manuel Martinez de Ubago Alvarez de Sotomayor
Delft, August 2019

Glosary

AGV	Automated Guided Vehicle
ALICE	Alliance for Logistics Innovation through Collaboration in Europe
ATA	Actual Time of Arrival
B2B	Business-to-Business
B2G	Business-to-Government
CBER	Consortia Block Exemption Regulation
CF	Contextual factors
CS	Current State
DF	Driving forces
DI	Digital Internet
DMM	Digital Maturity Model
DMPC	Dynamic Model Predictive Control
ETA	Estimated Time of Arrival
ETD	Estimated Time of Departure
EU	European Union
GHG	Greenhouse Gas
HLH	Hamburg Le Havre
ICT	Information and Communication Technology
IMOFAL	International Maritime Organization Facilitation of International Maritime Traffic
IPIC	International Physical Internet Conference
IQR	Interquartile range
IT	Information Technology
L1	Level 1
L2	Level 2
L3	Level 3
L4	Level 4
MRQ	Main Research Question
NOLI	New Open Logistics Interconnection
OLI	Open Logistics Interconnection
PESTEL	Political, Economic, Societal Technological, Environmental and Legal
PI	Physical Internet
PoR	Port of Rotterdam
PCS	Port Community System
PCL	Port Centric Logisticsc
PMS	Port Management System
RFID	Radio Frequency Identification
SRQ	Sub Research Question
TCP/IP	Transmission Control Protocol/Internet Protocol
TFEU	Treaty of the Functioning of the European Union
UNCTAD	United Nations Conference on Trade and Development
US	United States

Executive Summary

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, to the best of the author's knowledge, nearly unexplored.

Since maritime ports are considered as key global trade enablers, the proposed research aims to provide insights into possible scenarios of the evolution of maritime ports under the influence of the development of the PI. This is done by answering the following Research Question: *"What are the scenarios for the development of maritime ports under the Physical Internet?"*. The sub-questions that arise from the previous are:

1. *What are the main PI characteristics?*
2. *How do the main PI characteristics influence the evolution of maritime ports?*
3. *What are the main external factors affecting the PI characteristics and how?*
4. *How do maritime ports evolve for each scenario?*

Methodology *Chapter 2*

In order to answer these questions, the thesis takes the following approach. Firstly, the main characteristics of the Physical Internet are outlined by means of literature review and interviews with experts in the field. These are then particularized to the context of maritime ports. The resulting PI Port framework shows how the development of the different PI characteristics influence the evolution of a port towards a "PI Port". The second stage consists on the elaboration of contextual scenarios for the development of the Physical Internet. These scenarios, along with the previous particularized framework or "system", are used as input for a Delphi survey. In this questionnaire, experts are asked to give their opinion on the level of development of the different PI characteristics, for each scenario. From the results, an evolution path of the port towards a PI Port can be outlined, as a function of the development of the PI characteristics.

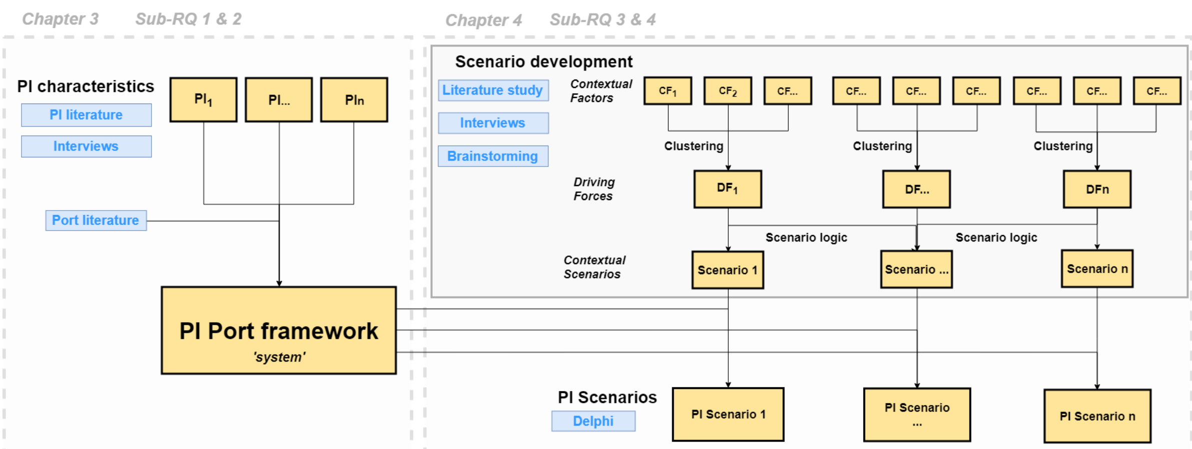

Figure 1: Overview of the approach taken for this thesis.

PI Port framework *Chapter 3*

To derive the main PI characteristics, an in-depth literature review of the Physical Internet was conducted. The findings were complemented with 4 interviews with experts in the field. The characteristics from both sources are summarized in the following table.

Table 1: Summary of the different PI characteristics from the literature review and the interviews with experts.

Literature Review	Interview 1	Interview 2	Interviews 3 & 4
Modularity	Modularity	Certified Open Logistics Service Providers	System Level Functionality
		Smart Data-Driven Analytics, Optimization & Simulation	
	Openness	Open Logistics Decisional & Transactional Platforms	Governance
Collaboration		Global Logistics Monitoring System	
		Certified Open Logistics Facilities and Ways	
	Automation	Standard Logistics Protocols	Network Services
Interconnectivity		Containerized Logistics Equipment and Technology	
	Decentralization	Unified Set of Standard Modular Logistics Containers	Nodes

Considering the different levels of abstraction from both literature and interviews, and the lack of consensus in the terminology used in the Physical Internet, the identified characteristics were clustered into three distinct dimensions. These resulted from a generalization or up-scaling of the definitions given from the characteristics initially derived from literature. Three distinguished PI layers are identified: (1) Digital layer; (2) business and contractual layer; and (3) physical and operational layer.

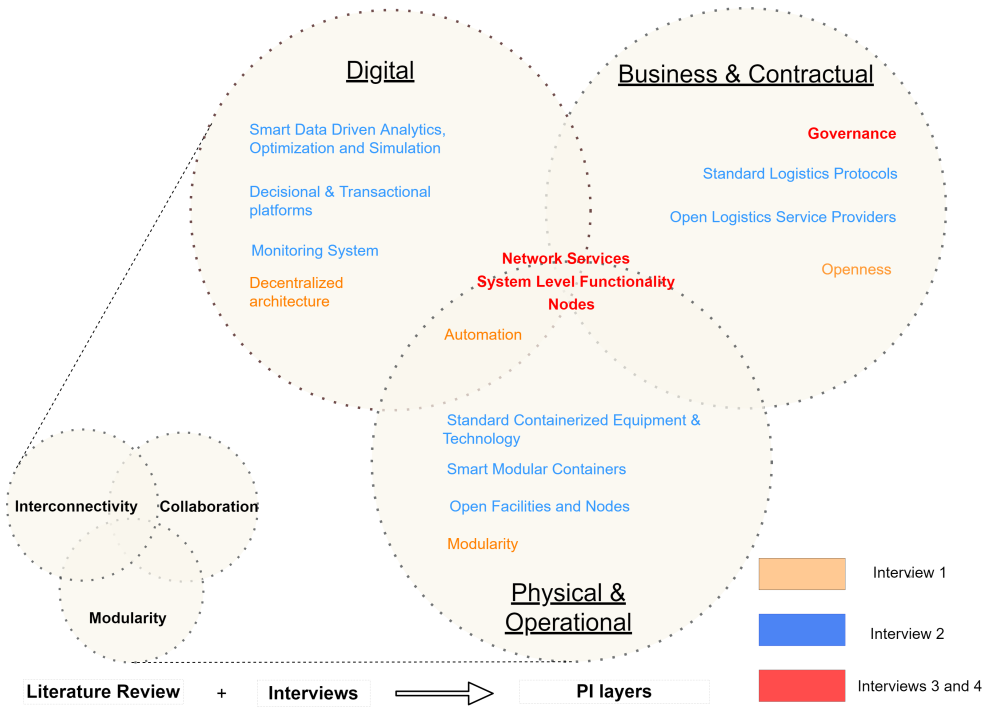

Figure 2: Resulting characterization of the Physical Internet from the Systematic Literature Review.

For simplicity reasons, and considering the importance to avoid misunderstandings by the panellists from the subsequent Delphi stage, the three layers were renamed into three dimensions. These would be considered as the "PI characteristics", and their definition is the following:

- **Operational dimension.** This dimension refers to how transport is physically executed and operated by the different elements in the transport network, from hubs, warehouses, vehicles or handling equipment.

- **Digital dimension.** This dimension deals with the digital connectivity of the different players in the logistics network. A system is in place so that the actors can share information, communicate with each other and make decision for optimized transport networks.
- **Governance dimension.** Businesses need rules and protocols in place for exchange of data, and goods within the Physical Internet, from individuals and smaller businesses to the bigger companies. The "Governance Dimension" refers to this set of rules for a cooperative, safe an reliable PI environment.

Based on the previous generalized characterization of the Physical Internet, the same three dimensions were tailored to the context of maritime ports as nodes in freight transport systems. First of all, and idea of how a hyperconnected maritime hub would function under PI freight transport systems was envisioned. Based on this, a bottom-up path was generated to try to capture how the three PI characteristics or dimensions influence the evolution of a port into a hyperconnected maritime hub, or "PI Port". In an ideal condition, each dimension evolves independently from their Current State up to Level 4 and influence the level of "port connectivity". This was considered the "system" from which contextual scenarios would be constructed.

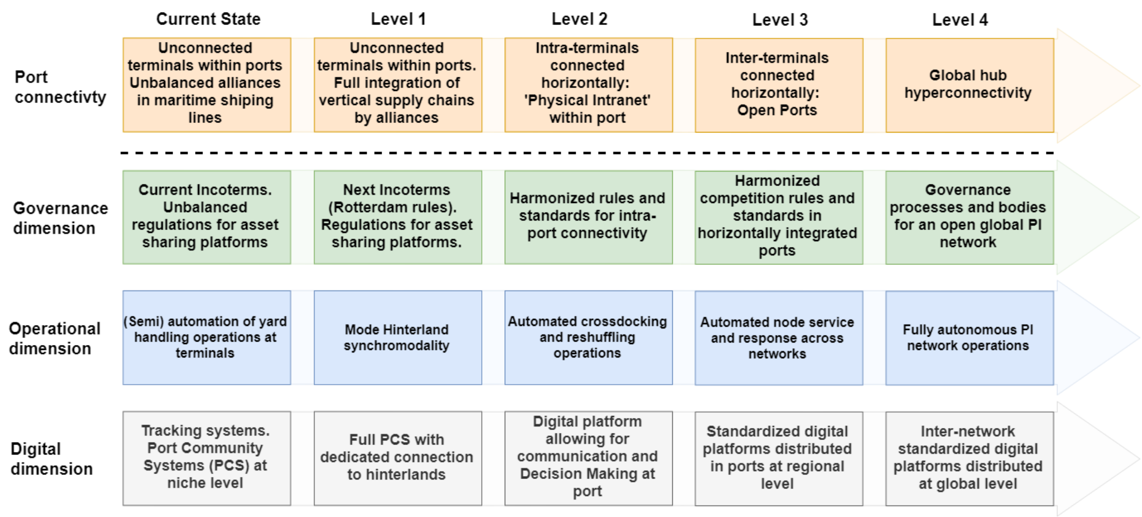

Figure 3: PI Port framework. Evolution levels of three dimensions which influence the development of port connectivity towards a hyperconnected hub, or "PI Port".

Contextual Scenarios *Chapter 4*

From literature, reports, the previously conducted interviews, and brainstorming sessions, 32 contextual factors (CF) which could potentially influence the PI characteristics were identified. Following the clustering into 7 driving forces (DF), these were assessed according to their relevance on the previous conceptualization or "system", based on their "impact" and "uncertainty".

Driving Force	Impact	Uncertainty
Global institutional integration	**Large**	**Large**
Flow patterns	Small	Large
Climate change	Small	Small
Technological innovations	Large	Small
Regulatory frameworks	**Large**	**Large**
Business models	Small	Small
Demographic changes	Small	Small

Four contextual scenarios were outlined as a combination of the directions that each selected relevant driving forces ("Global institutional integration" and "regulatory frameworks") would take.

PI Scenarios *Chapter 4*

The contextual scenarios were used, together with the resulting PI Port framework, as input for a two-round Delphi survey. Experts were asked to select, for each scenario, the level of development of each of the three PI dimensions, for the years 2030 and 2040. This totalled 24 multiple-choice questions to answer on a five-point scale, besides the feedback asked at the end of each round. While experts had to select categorically a particular level (highest number of votes given by the mode), assigning quantitative values to their responses allowed to compute the mean and give further interpretation of the results. A minimization criteria was proposed to determine the level of "port connectivity", as a function of the three PI dimensions, for years 2030 and 2040. The table below summarizes the results outlined from the Delphi study, and presents the evolution level that the port reaches. Values in the left column represent the mean value of the PI dimensions and "port connectivity" from 1 (Current State) to 5 (Level 4), while right column represent the category with the highest percentage of votes (mode), for each question respectively.

Table 2: Summary of evolution levels of the port for all PI scenarios, for both the criterion of ratios (mean) and categories (mode) respectively.

Criteria		μ (mean)				Mode			
Dimension		Gov_1^T	Op_1^T	Dig_1^T	$Hub_{hyp,1}^T$	Gov_1^T	Op_1^T	Dig_1^T	$Hub_{hyp,1}^T$
Scenario 1	2030	2,80	3,05	3,30	**2,80**	3 (L2)	3 (L2)	3 (L2)	**3 (L2)**
	2040	3,75	3,95	4,35	**3,75**	4 (L3)	4 (L3)	5 (L4)	**4 (L3)**
Scenario 2	2030	2,00	2,65	3,00	**2,00**	2 (L1)	3 (L2)	3 (L2)	**2 (L1)**
	2040	2,65	3,65	3,60	**2,65**	3 (L2)	4 (L3)	4 (L3)	**3 (L2)**
Scenario 3	2030	1,90	2,55	3,00	**1,90**	2 (L1)	3 (L2)	3 (L2)	**2 (L1)**
	2040	2,50	3,00	3,60	**2,50**	3 (L2)	3 (L2)	4 (L3)	**3 (L2)**
Scenario 4	2030	1,60	2,20	2,25	**1,60**	1 (CS)	2 (L1)	2 (L1)	**1 (CS)**
	2040	2,20	2,75	3,00	**2,20**	2 (L1)	3 (L2)	3 (L2)	**2 (L1)**

From the results of the previous table, the evolution path of "port connectivity" can be outlined by joining the levels for the present year (assumed to be 2020), the year 2030 and the year 2040. The evolution path of "port connectivity" is represented, for each PI scenario, by the mean (continuous lines) and the mode (dashed lines). Given the similarities in their evolution path, PI scenarios 2 and 3 are discussed together.

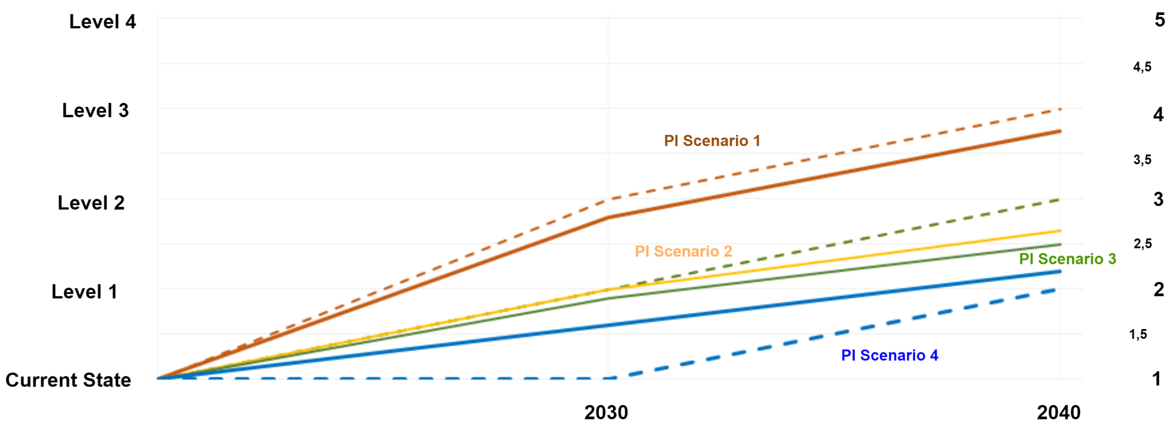

Figure 4: Evolution of "port connectivity" for each of the four scenarios.

PI Scenario 1

The most optimistic evolution path was reflected in PI scenario 1, which was dominated by a favorable global institutional environment and fast regulatory frameworks that allow for a quick development and adoption of new technologies. In this context, the port becomes open internally by 2030, which means that global alliances have fully integrated their vertical supply chains, while the terminals interconnect horizontally within the port. This "Physical Intranet" at the entire port community level scales up during the following 10 years, eventually reaching nearly all ports at the regional level. For the case of the Port of Rotterdam, this would mean including neighboring ports within the Hamburg-Le Havre range.

PI Scenario 4

The flattest or slowest evolution path was given by PI scenario 4, which involved a challenging global setting of high protectionism between major power blocks and slow regulatory frameworks lagging behind market developments. Given this context, the level of connectivity remains at the shipping line level, where alliances have vertically fully integrated their own dedicated terminals and supply chains. This could be seen as a form of "Physical Intranet" at the firm level from the perspective of the shipping lines.

PI Scenario 2 & 3

PI scenarios 2 and 3 lied in between the other two. In 2030, "Physical Intranets" at the firm level are reached, which involve a complete vertical integration of supply chains within maritime alliances.During the next 10 years, dedicated terminals are slowly becoming more open to connect horizontally with other competing nodes. This development is slightly faster in Scenario 2 than in Scenario 3, yet the "Physical Intranet" at the port community level has not fully been unlocked in any of the two future hypothetical futures.

Conclusions from the results

Several conclusions that can be drawn from the results:

- From the PI scenarios it seems that the "Governance Dimension" is lagging behind, and adopting the minimization rule used in this research, this dimension would be the most critical out of the three PI dimensions.
- From PI Scenario 2 and PI Scenario 3, it seems that experts, on average, penalized more an environment of high protectionism (from Scenario 3) than a future with regulatory frameworks lagging behind market developments (from Scenario 2).
- Level 4, the ultimate stage of the framework and considered as the full global roll-out of the Physical Internet, is never reached under any of the four scenarios considering the minimization rule. Looking into the results from the Delphi study, under the most optimistic scenario in terms of global institutional integration and regulatory frameworks (PI Scenario 1), the "Physical Internet" in ports as nodes of freight transport systems is achieved at the regional (European) level at most.

Implications for the Port Authority of Rotterdam

Given the previously visualized results, and without the aim to provide an exhaustive policy roadmap, general recommendations were given to maritime ports in general, yet particularized for the Port Authority of Rotterdam, as the problem owner of this research.

- Maximize the slowest evolving PI dimension. Assuming that maximizing the level of port connectivity from the PI Port framework is desired, a high focus should be put on the "Governance Dimension", given the results of the scenarios considered. As particular measures, the Port

Authority could firstly play an active advisory role by evaluating and monitoring the implementation of the Rotterdam Rules in the Netherlands and neighboring countries within Europe. Secondly, regarding the CBER, the Port Authority could either promote its extension in 2020, or bring in together other stakeholders (i.e. port authorities or shipping line representatives) to discuss a more flexible version of the current CBER, while still in compliance with Article 101 of the TFEU.
- Avoid leaving the other PI dimensions overlooked. As a forerunner regarding the "Operational Dimension" and the "Digital Dimension", the Port Authority could play an advisory role with other port authorities and stakeholders so that the scaling up of the Physical Internet beyond port domains to a regional level can become a reality in the future.

These recommendations are still compatible with the current goal of the Port Authority of Rotterdam, which is to "enhance the competitive position of the port as a transport hub, in terms of volume and quality". Ports can attract more cargo while increasing their levels of "port connectivity" within and beyond their domains.

Conclusion *Chapter 5*

The research goal of this thesis was formulated as follows: *"Generate contextual scenarios that influence the development of a port into a PI port so that Port Authorities can consider such influence in their strategic policies and therefore adapt accordingly".*

To fulfill this objective, the identified main Research Question (MRQ) was *"What are the scenarios for the development of maritime ports under the Physical Internet?".*

To answer this question, a two-round Delphi study was conducted. From the results of the survey, four "PI Scenarios" were generated from the resulting Delphi study. They outline the evolution path of port towards a hyperconnected hub or "PI Port" as a function of the development of the different elements of the Physical Internet depicted in this research.

The port has the fastest evolving path in PI Scenario 1, the most optimistic of them all in terms of the global institutional environment and the speed of regulatory frameworks that enable new technologies. In this case, the Physical Internet is achieved at the regional level in the year 2040. The most pessimistic situation is reflected in PI Scenario 4, with a contextual environment marked by a challenging global setting or high protectionism and slow regulatory frameworks lagging behind. Only "Physical Intranets" are achieved by the year 2040 at most, with the port remaining unconnected internally. PI Scenarios 2 and 3, with the former evolving slightly faster than the later, lay in between the other two. By 2040, dedicated terminals are slowly becoming open horizontally with other competing terminals inside the port.

Reflection on the thesis *Chapter 6*

The intermediate and resulting findings from this research open room for a rich debate in the context of the Physical Internet and maritime ports. It is relevant however to reflect on the methodology and the outcomes outlined in this thesis, from which further research can build upon.

Reflection on the methodology

- The body of **PI literature** was considered to be sufficient, and a categorization criteria based on the methodologies of the publications was used. However, the approach to derive the main PI characteristics from them, based on a counting technique, was too rigid and drew an incomplete view of the Physical Internet. This was however well complemented with the interviews with experts.
- The body of **port literature** is much larger than the context of the PI. Without the aim to conduct a through literature review, the research context in the role of ports and port development was considered as sufficient throughout the thesis. Nevertheless, without a strict

approach in the selection of the publications, relevant contributions might have been overlooked.

- Regarding the **interviews** with experts in the PI, the chosen candidates met the expert criteria and spoke on behalf of a larger community. For that reason, their opinions of the PI were considered to be sufficiently comprehensive and allowed to complement the findings from literature. An unstructured format was followed for the sessions, allowing experts to freely express their idea of the PI. This was done at the cost of a poorly managed timing of the sessions, with little space at the end to discuss the contextual factors needed for further stages of the research.
- For the **scenario development**, instead of participatory studies, which are commonly used for explorative or contextual scenarios, a scenario logic approach was used instead. An adapted methodology from the guidelines of Enserink et al. (2010) allowed to quickly generate contextual scenario, based on a combination of the development of different relevant driving forces. Without an extra step to ensure orthogonality among the clustered driving forces, inter-dependencies were identified. Based on this, and coupled with the decision to fix the maximum number of scenarios, which would be used for a further Delphi study, the logic reasoning behind the selected relevant driving forces could have been biased.
- The steps conducted for the **Delphi** significantly stirred around the fear of fatigue and non-response by the author. The condition of "knowledgeable" expert in the PI was considered to be enough to consider a candidate as knowledgeable in maritime ports. In this sense, a rigorous evaluation step to check the suitability of experts was not made. This resulted in a relatively high response-rate, at the expense of the shortcomings mentioned above. panellists were surveyed in a categorical five-point scale in an user-friendly tool. Lastly, the Delphi was used as an opportunity to get feedback on the different stages used in this thesis, allowing to enrich the debate around the PI and its influence on maritime ports.

Reflection on the outcomes

- The **PI Port framework** was the result of several brainstorming sessions which built upon the insights from the literature review and the interviews with PI experts. It is important to remark that the evolutionary model focuses on a generic port and its hinterland, while avoiding to include the sea connection to another port. In line with the previous, its applicability to any port could be subject to debate. Moreover, it fixes the ordering and the content of the cells, giving little room for other developments aside from the proposed in the three PI dimensions, which could be limited on their own. Looking into the PI dimensions, their evolution were assumed to be independent from each other, yet from the Delphi outcomes, this assumption could have turned to be wrong. Lastly, the PI developments proposed in the framework lacked the use of theoretically-founded models that could have given robustness to the framework.
- From the selected driving forces, four **contextual scenarios** were outlined and used as input for the Delphi survey. Inter-dependencies were spotted by the panellists, which suggests that another combination of driving forces could have envisioned more comprehensive contextual scenarios. Yet, any logic reasoning could have given different, both arguable and valid, set of driving forces.
- Any shortcoming in the previous outcomes could have cascaded to the resulting **PI scenarios**. In line with the previous, the Delphi fed on the contextual scenarios, meaning that another combination of driving forces could have drawn different evolution paths. Moreover, considering that no strict evaluation check of the suitability of experts in the field of both PI and port was made, the validity in the responses, and therefore the evolution path of the PI dimensions, should also be taken with caution. Lastly, the evolution path of "port connectivity" followed a minimization rule, a coherent and conservative approach which took into account the logic followed behind the construction of the PI Port framework.

Recommendations for further research

The resulting outcome of this work tried to make a relevant contribution to fill in the identified research gap: *"current literature does not provide insights into the way possible future developments of the Physical Internet can influence the evolution of maritime ports"*.

The findings from this thesis focus not only on the final outcomes but also on the intermediate steps, opening room for insightful research that can further build upon the topic of the Physical Internet in the context of maritime ports. Considering the large room open for research within the topic of the PI, and based on the discussions above, the following are proposed for further research from the context of this thesis:

- The use of **systematic literature reviews** should be considered to merge both the Physical Internet and the evolution of maritime ports. This way, they chances to overlook important characteristics and levels of abstraction within both topics, especially with the later, might be lower.
- **For more robust and theoretically-grounded frameworks in the field of PI**, applicable to maritime ports or other elements within freight transport systems in general, further research should **use theoretical models**.
- With the purpose to **expand the number of scenarios**, extra Delphi rounds could be used to generate a larger number of explorative scenarios, were consensus among participants would not be strictly necessary. An alternative could be, if fatigue plays a big role throughout successive rounds, to use in-person Delphi workshops, were misunderstandings or any potential question arising from the panellists could be solved. The SENSE workshops or the annual IPIC conference could be suitable moments for those sessions.
- Building upon the results herein presented, it is important as a next step to **quantify the impact of the evolution of the Physical Internet in maritime ports**. Estimating future cargo flows within the context of the PI for each scenario could further help Port Authorities design appropriate policies, strategies and related infrastructure. From here, identified potential threats and opportunities based on the different PI freight networks depicted per scenario, a roadmap of actions that ensure maritime ports succeeding in their strategic goals could be proposed.

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Introduction

With the goal to improve efficiency of transport and logistics, the Physical Internet (PI) is a novel vision that aims to reshape the way physical objects are currently moved, stored, realized, supplied and used (B. Montreuil et al., 2010). It was formally defined as an "open global logistics system founded on physical, digital and operational interconnectivity through encapsulation, interfaces and protocols" (B. Montreuil, Meller, & Ballot, 2012). Its introduction sparked research collaboration between academia, industry and governments to progressively gain and share knowledge on the topic. The ALICE project, an European Technology Platform recognized by the European Comission, developed a roadmap to achieve a 30% improvement of end-to-end logistics efficiency by 2040, with the vision of the PI in mind (ALICE, 2018).

Nevertheless, despite these efforts, the concept is still in its early stages and many questions still need to be answered. Because of the complexity and the change in paradigm it implies (B. Montreuil et al., 2010), an idea of this magnitude is expected to have a profound effect on all actors involved in freight transport systems. With 80% of the total share of global trade, which surpassed 10,7 billion tons of freight in 2017 (UNCTAD, 2018), being done over sea, maritime transport could be significantly affected. In this sense, maritime ports as they are known nowadays could significantly change over time under the influence of the Physical Internet.

In this chapter, freight transport systems are briefly defined. Following this introduction, the problem statement of the thesis is outlined, which involves the Port of Rotterdam as the problem owner. A research context is provided, which allows for an identification of the research gap, research objectives and research (sub)questions. The chapter concludes with the outline of the rest of the thesis.

1.1. Current freight transport systems

It is important to understand what freight transport systems actually entail, since these are not limited to the modes of transport or the network infrastructure in which they operate. Taking a broad definition of *system* as "a set of entities with relations between them" (Backlund, 2000), *freight transport systems are composed of physical and non-physical aspects, that is, the infrastructure, services, public policies and equipment that make the flow of goods possible.* They can be considered as highly complex and continuously evolving according to their demand and environment (Halim et al., 2012).

As enablers of global trade, these systems are multi-layered according to the actor making a decision, from manufactures and consumers to the transport carriers. Five layers or "markets" can be distinguished in freight transport systems (Tavasszy, 2006): Production/consumption; trade (sales and sourcing); Inventory location; transport services; and routing. These are represented in Figure 1.1, where the arrows on the left and right represent the demand and supply effect of each layer, respectively. As can be seen, the upper layers refer to spatial equilibrium between supply and demand of products, whereas the lower layers represent the transportation networks, in which the different modes (road, airway, rail, maritime,...) perform their transport activities through links and nodes[1]. Each actor has its own goal and make its own decision, being linked with others through many interconnections, interactions and inter dependencies (Crainic et al., 2018).

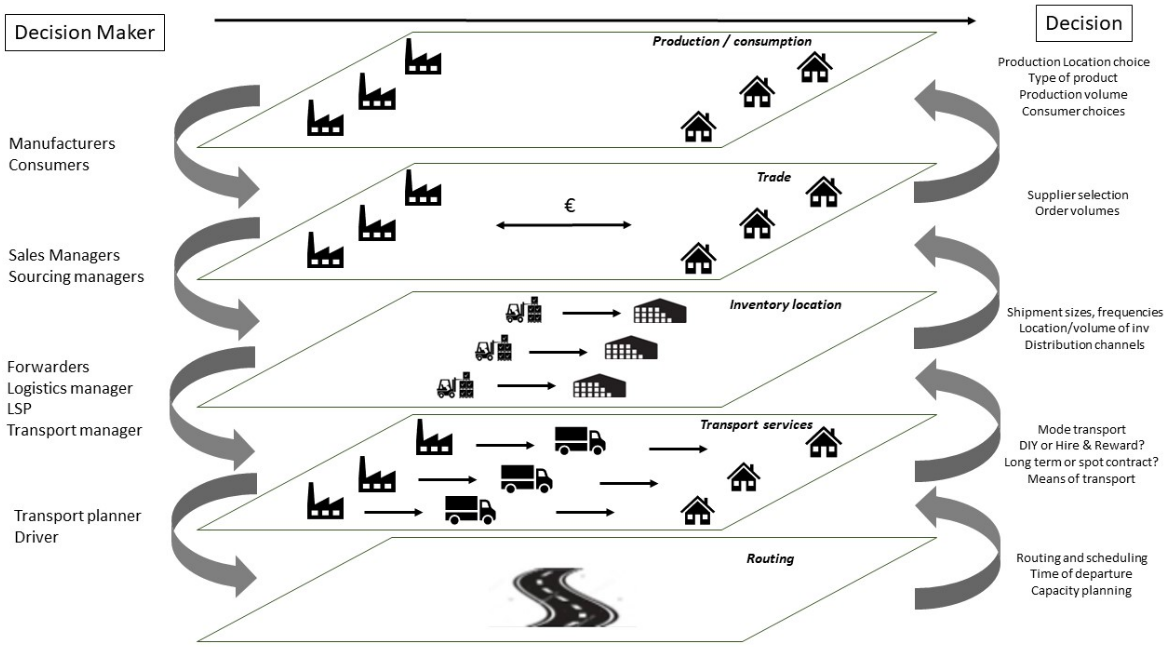


Figure 1.1: Conceptual framework of freight transport systems. Adapted from Tavasszy (2006).

Transport and logistics services of companies have focused their attention into optimization given the available resources, based in some cases on consolidation of shipments and taking advantage of economies of scale. Yet, dedicated logistics services of companies have in many cases shared the same transport infrastructure. This has resulted, according to some academics, in inefficiencies of the logistics networks by "over-use of means often dedicated to organizations" (Sarraj et al., 2014). An illustrative example is depicted in the figure above, which shows how decisions are firm-focused. Each company in the upper layers deals with their own dedicated warehouses and terminals, and try to optimize their own dedicated transportation network (layers 3 and 4). These must, however, share the same infrastructure in the transport networks (layer 5).

By breaking these traditional proprietary models, the Physical Internet could be seen as a potential alternative to the usual "winner takes all" (Ballot, 2019). A change in the way current freight transport systems are conceived nowadays could however imply a profound and still uncertain reconfiguration for the different parties involved, something that these need to be able to predict and adapt from through operational, tactical and strategic policies and investing decisions. For a player such as a maritime port, these can range, among many others, from newer infrastructure developments, not only on its domain but also on its hinterland connectivity, to organizational changes or IT investments.

[1] The term network refers to the framework of routes within a system of locations (nodes). The route refers to the single link between two nodes that are part of a larger network through the different modes (Rodrigue et al., 2016).

1.2. Problem Statement

The maritime sector in general, and ports in particular, are highly asset and capital intensive (Rodrigue, 2010). Port infrastructure is expensive, and the associated high investments result in long payback periods. For this reason, it is crucial that port authorities are able to cope with future uncertainties so that they can take them into account in their strategic decision making, and therefore justify such investments. A modern method for grappling with uncertainties is to construct scenarios. In words of Hammond (1998), from his book *Which World?*, these are defined as "carefully posed stories that describe plausible alternative futures, often supported by reams of data and the intuitions and experience of experts and scholars". In this sense, scenarios can be elaborated by ports with respect to future global maritime freight systems so that proper strategic decisions can be made.

However, to the best of the author's knowledge, **the study of the Physical Internet in the context of maritime ports has remained nearly unexplored.** This raises questions about the way maritime ports will look under PI freight transport systems, and ultimately whether they will benefit from it or not.

1.2.1. Port of Rotterdam

Special interest in the PI has been shown by the Port Authority of Rotterdam, which will function as the *problem owner* of this research. The PI has been identified by the Port Authority as a promising solution for a more efficient logistics system[2], and they are interested in the potential impact it can have on the port itself.

Situated directly on the North Sea, the Port of Rotterdam (PoR) is considered one of the major contributors of economic prosperity not only in the Netherlands, but also in Europe. With an area of almost 13.000 hectares, the entire port employs approximately a total of 180.000 jobs and accounts for 3,3% of the Dutch GNP (PoR, 2011), reaching a turnover of nearly 710 million euros in 2017. Therefore, the impact of any change in the port cannot be negligible.

The PoR is currently ranked as the largest port in Europe and the 8th largest in the world (PoR, 2014). Nevertheless, when comparing ports vis-a-vis other ports in terms of operational performance (i.e., throughout), the Hamburg-Le Havre (HLH) is usually considered [see Figure 1.2], because they compete for similar types of cargo and vessels to serve the same hinterland (Nijdam & van der Horst, 2017). Being one of the most analysed port ranges of competition (Wiegmans & Dekker, 2016), ports in this area compete to serve Northern, Central and Eastern Europe.

Figure 1.2: Main ports in the Hamburg-Le Havre range. Source: author.

[2]See video by the Port of Rotterdam, where they consider the Physical Internet as a the potential "next big thing".

The Port Authority identified in its strategic vision, known as "Port Vision", major trends that can affect its position as a major European Hub, and therefore have an impact on the rest of stakeholders, from government to citizens and users of the port infrastructure (PoR, 2011). Enhancing the competitive position of the port as a transport hub, in terms of volume and quality, is of upmost importance for the Port Authority (PoR, 2017). In order to do so, the PoR elaborates future scenarios to assess their potential effect on the port, from future global freight transport systems an their impact on the container industry (PoR.c, 2018) to short-term political turmoils such as the upcoming Brexit[3]. In fact, the already mentioned strategic vision of the Port Authority resulted from a thorough study of trends and developments which were considered to be relevant for the development of the port and industry (PoR, 2011). Foreseeing any other possible future changes in the port domain is crucial so that the Port Authority can identify threats and opportunities to remain a major transport hub. In this sense, the study of scenarios related to the PI becomes relevant for the *problem owner* of this research.

1.3. Research Context

As already mentioned, the study of the PI in maritime freight transport systems seems, to date, to be unexplored. This section serves not to dive into the entire literature of the different topics, but rather to provide some context on the subject of the PI, maritime ports and scenario development. From here, a research gap has been identified, which allows for a formulation of a research question of special relevance in the academic field.

1.3.1. The Physical Internet (PI)

As already mentioned, the Physical Internet is a novel concept that is aiming at radically transforming the way physical objects are moved, stored, realized, supplied and used (Montreuil, 2009). The first formal scientific work came by B. Montreuil (2011), where the author exposed a total of thirteen symptoms related to current supply chain and logistics practices. These result in economical, environmental and societal issues that, according to the author, needed to be addressed to avoid "hitting the wall".

The PI was presented as a potential solution to address these issues, and its introduction was a call for action for academics, industry and government. In short, the PI aims to organize the transport of goods similar to the way data packages flow in the digital internet (E. Ballot, Gobet, & Montreuil, 2012). Through sharing of resources such as assets and data, and designing of interfaces and protocols for seamless "interoperability", the transport of goods would be optimized with regard to costs, speed, efficiency and sustainability. As in the Digital Internet (DI)[4], where fragmented packets are automatically sent through different routers, goods could be encapsulated in modular containers and be sent throughout a network of open hubs towards their final destination (Aroca & Pruñonosa, 2018). The relationship between the DI and the PI will be further explained in Chapter 3.

The first simulation study, based on product distribution flow of the two top food retailer in France from their top 100 suppliers, showed inspiring results about the potential of the PI. Cost savings ranged from 4% to 26%, and there was a threefold reduction in greenhouse gas emissions using more efficient road transport (E. Ballot, Gobet, & Montreuil, 2012).

Yet, to achieve such vision, vast knowledge needed to be gained first on all levels. Besides the manifesto, the starting point was perhaps done by B. Montreuil, Meller, and Ballot (2012), which outlined the main "foundations" or building blocks of the Physical Internet. Some publications focused on designing, from a conceptual point of view, how the nodes or hubs in the PI could look like, such as

[3] See Handbook Brexit for Dutch ports.

[4] For this research the Digital Internet is defined as a system of interconnecting IT networks based on a set of standardized protocols, the most famous of which is the TCP/IP, used to route standardized data packets.

Meller et al. (2012), E. Ballot, Montreuil, and Thivierge (2012), or B. Montreuil et al. (2013). B. Montreuil, Ballot, and Fontane (2012) and Colin et al. (2016) tried to adapt the layered structures from which the Digital Internet protocols work to a PI context. Sarraj et al. (2014) worked on the analogies between DI and PI hubs. Business models, as well as new regulatory frameworks have also been targeted as an important issue to address in this new logistics paradigm (B. Montreuil, Rougès, et al., 2012). Up to sixth editions of the annual International Physical Internet Conference (IPIC) have been celebrated to gather experts internationally and encourage knowledge sharing and building on the young topic (IPIC, 2019). On European level, under the so-called ALICE initiative, regular meetings and workshops are organized to reach consensus around the PI vision and the next steps it needs to undergo in the implementation of the overall vision (ALICE.b, 2018).

Despite the quick increase in the body of knowledge of this new vision, **no publications have been found on maritime ports and how these can be affected by the Physical Internet**. Only Aroca and Pruñonosa (2018), building upon the analogies between the DI and PI hubs, has been found to link the role of seaports as a "hyperconnected PI hub" from an operational perspective. The PI can be considered to be in a pilot stage from a conceptual point of view, with small number (albeit increasing fast) of conference papers and very limited project implementations (Domański et al., 2018). For that reason, complete consensus on the characteristics of the PI might still be lacking. Therefore, the need to conduct a systematic literature review on the Physical Internet to derive its main characteristics is justified, and is fully outlined in Section 3.1.

1.3.2. Maritime Port Systems

Unlike the Physical Internet, literature is rich and varied in the field of maritime ports. For that reason, it is preferable to give context regarding different research categories within maritime ports that are relevant for this thesis. These relate to their roles in freight transport systems and the way they have developed over time.

Role of maritime ports in freight transport systems

Historically linked with city developments, maritime ports have evolved to function as critical facilitators of international trade, not only having a big impact on the local economy, but affecting the way that regional and national economies operate (ITF, 2015). Ports can be seen as highly complex systems due to the large and diverse number of stakeholders and types of services they offer.

Due to its multifaceted nature, a clear definition on ports[5] does not exist. Institutional, administrative or organizational disparities hinder a comprehensive approach to maritime ports in general (Bichou & Gray, 2005). From a network perspective, major ports can act as hubs or nodes of the entire transport chain. Because of the vagueness of the term *hub* used by practitioners and academia, an adapted definition of maritime hub from Song and Panayides (2012) is taken:

(1) A nodal point of cargo transit or transshipment, located to connect land and sea, and assuring flawless door-to-door cargo movements; (2) a principal distribution centre functioning as a temporary storage and sorting, and (3) a place creating and facilitating value-added services on the regional and/or international scale.

Considering the framework by Tavasszy (2006), Figure 1.3 serves as a simple illustration of the importance of maritime ports in current global freight transport systems:

[5]For practical reasons, the terms *ports*, *seaports*, and *mainports* will be used indistinctly throughout this thesis.

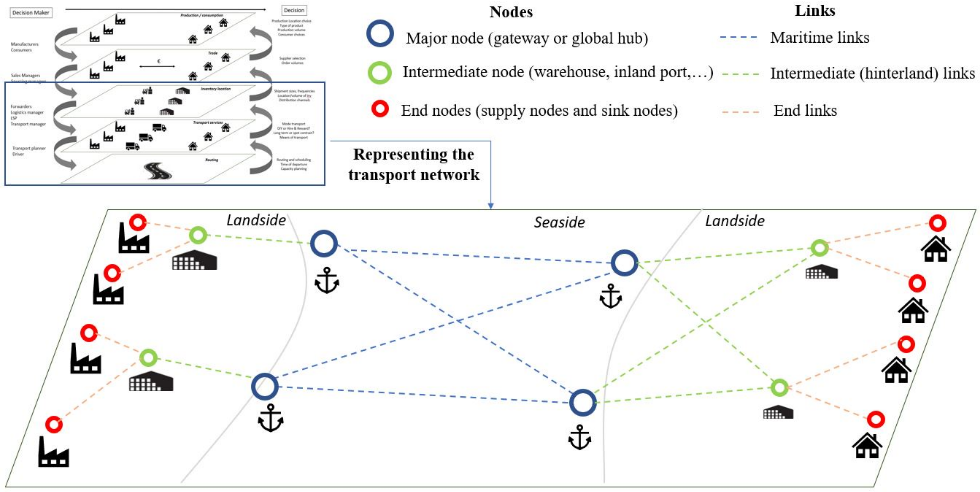


Figure 1.3: Example of transport network with ports functioning as hubs in freight transport systems. Adapted from Tavasszy (2006).

Nodes of different scale are connected through links or arcs in the network. In the context of maritime networks, a link between at least two ports, one as the sending end and one as the receiving end, is necessary. Because production and consumption of goods do not take place in the same location (Nijdam & van der Horst, 2017), the need for exchange of cargo, especially at an international level, makes ports vital nodes in transport chains. Extending on the framework from Tavasszy (2006), as a consequence of (international) trade, transport services are demanded, and because the ports act as vital nodes, port services are demanded as well. Yet, these are not only limited to serving as nodes of the transport network. They are also a location of value-added industry and logistics activities (Nijdam & van der Horst, 2017). For bigger global ports such as the Port of Rotterdam, they act as central hubs in the entire transport network, where flows are concentrated and economies of scale are achieved. This is the classic structure of a hub-and-spoke network (Rodrigue et al., 2016).

From the previous, it becomes clear that the main function of a port is to serve as a node in the transport chain, because it (1) connects land with sea and different modes of transport; (2) the demand for transport is spatially diverse; and (3) ports can facilitate temporary storage if needed (Nijdam & van der Horst, 2017). Since ports have developed into "clusters of economic activities" (de Langen et al., 2007), a second important function of a port is outlined, which is to act as a location for value-added economic and logistics activities, such as warehousing. This can be somewhat related to the Port Centric logistics (PCL) concept, which was defined by Mangan et al. (2008) as "the provision of distribution and other value-adding logistics services at ports". This idea is based on the notion that the port acts as the sole point at which goods are imported, stored and distributed inland, which would ultimately remove unnecessary supply chain legs (Valantasis Kanellos & Song, 2015). The Port of Rotterdam has been a forerunner of this concept since the 1980s with the so-called Distriparks (Pettit & Beresford, 2009).

There are several actors playing a role in maritime ports, each with their own function (Nijdam & van der Horst, 2017):

- **Deep-sea terminal operator.** Dedicated to the (un)loading of ships and the temporary storage of goods. Its main customers are the shipping lines and the importing/exporting companies (shippers).
- **Shipping line.** Operating ships and providing shipping services as the core business, a distinction can be made between liner shipping and tramp shipping. The former offers transport with fixed route and schedule, and is mainly offered for containers, cars and RoRo-cargo.

In the later there is no fixed schedule and is offered mainly for commodities such as oil and iron ore. The main business is to sell capacity of ship to their customer. That is, the shipper or, in case the logistics management is outsourced, intermediaries such as forwarders or shipping agents. Examples of major deep-sea shipping lines can be APM-Maersk, COSCO or CMA-CGM. The company DFDS can be an example of a short-sea shipping line in Europe.

- **Forwarders.** Based on its knowledge of the transport market, its main role is to provide door-to-door transport solutions for the shipper. Also known as Logistics Service Provider, the forwarder can (1) select the transport company and negotiate freight rates; (2) consolidate small shipments into larger loads and present them to transport carriers; and (3) arrange all the necessary documentation (Ducruet & Van Der Horst, 2009).
- **Shipbroker.** Acting as another intermediary in the port, this type of broker represents the shipowner and is responsible for the business of the ship. That includes obtaining cargo from shippers, arranging port activities in the ship (i.e. loading of cargo) and paperwork such as customs clearance or insurance.
- **Transport carriers.** In the context of the port, these are companies that serve its hinterland by different modes, such as rail, road or inland waterways. Depending on factors such as the volume of cargo, distance to the next destination, or flexibility, one mode can be more attractive than other.
- **Providers of nautical services.** These are the companies that provide vessels with different services such as pilotage, towage, or mooring. Shipping lines are the main customers of these actors in the port.
- **Port Authority (PA).** As already described, it can be seen as the governing body and most important player in the port, responsible for the planning, development and safety of the port.

Looking into port authorities, literature is rich and diverse with respect to the role that these have played over time. Traditionally, PAs have been categorized into three headings: regulator, landlord and operator [see Baird (1995), Baltazar and Brooks (2001), Verhoeven (2010) and Centin (2012)]. Since the two major revenue streams of port authorities are land value (contract rent) and port throughput (port dues), the landlord function has been considered to be the primary role of port authorities (Verhoeven, 2010). The ever-changing environment has had serious effects on the traditional role of port authorities (Centin, 2012), with increased private participation within the port domains and merges between the major operators as crucial factors (Heaver et al., 2001). Many academics agree that the traditional role of port authorities has evolved into "acting as facilitators within logistics chains" (Centin, 2012).

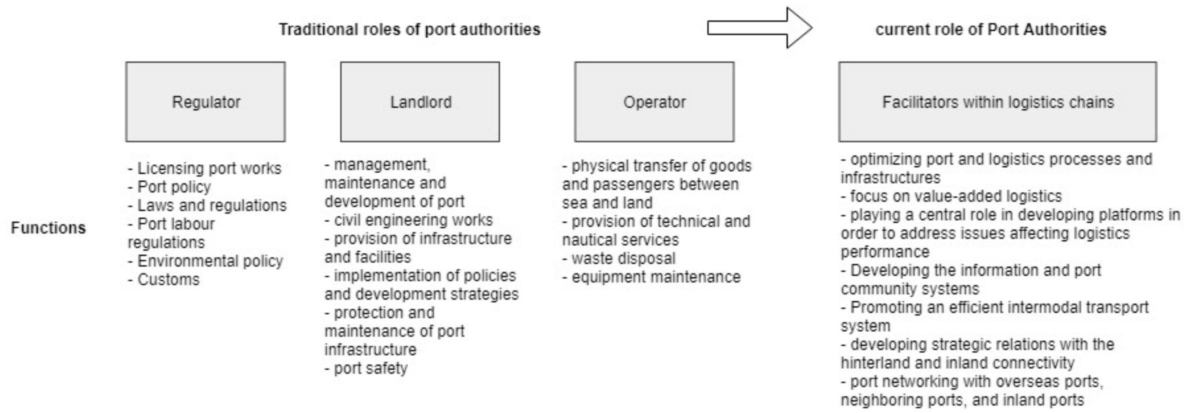


Figure 1.4: Evolving roles of port authorities. Adapted from Baird (1995), T. E. Notteboom and Winkelmans (2001), T. E. Notteboom and Rodrigue (2005), Verhoeven (2010), Centin (2012).

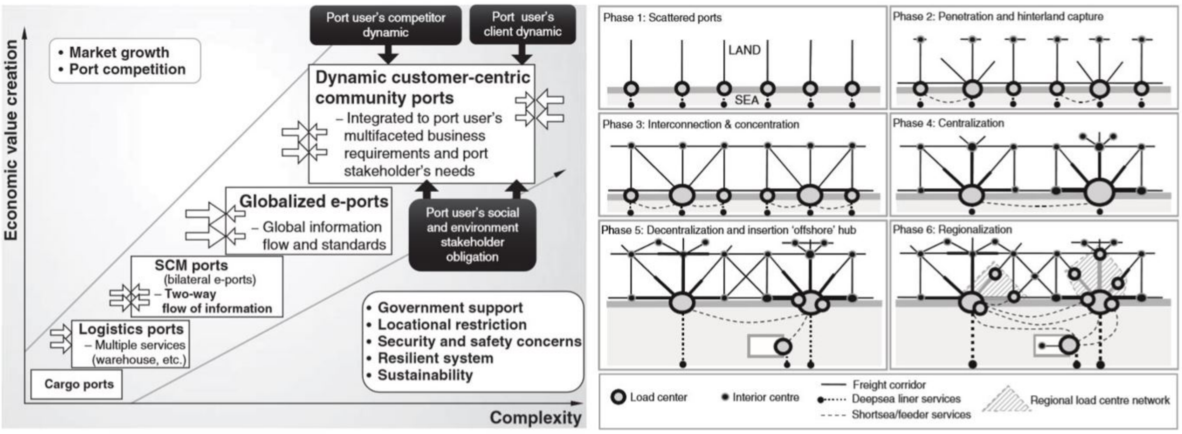
While acknowledging all the different roles that have been pointed out in the literature, the functions given by the Port Authority of Rotterdam are accepted for this thesis (PoR, 2009): (1) Development, construction, management and operation of the port and industrial area of Rotterdam; and (2) Promote effective, safe and efficient handling of shipping in the port of Rotterdam and the offshore approaches to the port.

Port development

Literature is also rich in the field of port development. Ports have initially been categorized by the UNCTAD into "port generations" or stages as an explanation of how these have adapted to incorporate technological, political and operational changes (UNCTAD, 1992). Three generations were proposed, which evolved from traditional (un-)loading activities (first generation) to a range of logistics and value-added activities (third generation) (Paixão & Bernard Marlow, 2003). A fourth stage (4GP) was added in 1999, as a result of technological changes and developments in working practices and the commercial environment that had taken place (UNCTAD, 1999). Academics have given however different interpretations to what the 4GP entailed (see Paixão and Bernard Marlow (2003); Verhoeven (2010)). A fifth generation ports model (5GP) was proposed as "customer-centric and community focused ports, with service deliverables related to port user's multi-faceted business requirements, while also taking care of community stakeholder requirements" (Flynn et al., 2011). A modified version of the concept from the 5GP was proposed to evaluate inter-port competition of the four major container ports in Asia (P. T.-W. Lee & Lam, 2015).

The UNCTAD approach has been subject to criticism. Bichou and Gray (2005) and Verhoeven (2010) criticized the generation approach since it generally fails, among other flaws, to reflect the composite reality of seaports by applying a rigid categorization. For instance, fourth generation ports can still be performing first generation-type functions by handling first generation-type cargo and ships. Others concluded that the UNCTAD model was fundamentally flawed (Beresford et al., 2004). Differential development can take place at individual terminals within a port, as a result of commercial pressures or goals of the different actors. The authors argued that the allocation of ports to a particular generation category might be problematic, since "all ports are, to some extent, unique". Moreover, "rather than in discrete steps, ports evolve continuously" and adapt to their external environment by continuously changing economic and trading patterns, new technologies, legislation, and port governance systems. Developing continuous steps for port next generation models remains challenging. A framework in which port generations evolve along a "port ladder" describing how leading ports are continuously adapting to new customer requirements, in line with an ever changing shipping and port environment, was presented by Lee and Lam (2016) [see Figure 1.5.a].

The development of ports could be also seen in phases from a spatial perspective. A well known framework is the "Anyport" model proposed by Bird (1980). In an initial stage, a small port site evolves as a product of evolving maritime technologies and improvements in cargo handling. In this sense, setting, expansion and specialization were the three major steps identified in the port development process. For large traditional ports, the model has been considered a valid interpretation of port development. Nevertheless, weaknesses were identified in this framework, such as the lack to include the inland dimension as a driving force in the dynamics of port development, as suggested by T. E. Notteboom and Rodrigue (2005). As a result, a phase of port regionalization was added and built upon the Anyport model, whereby the influence of the port extends beyond the port boundary by means of broader strategies which link the port to a wider market [see Figure 1.5.b]. The "gradual and market-driven" formation of a "regional load centre network" is the result of increased focus on inland accessibility, as the cornerstone of port competitiveness, and higher levels of integration between both maritime and inland transport systems, as suggested by Heaver et al. (2001).



(a) (b)

Figure 1.5: (a) Evolution path of ports according to added value and complexity (Lee & Lam, 2016). (b) Spatial developments of a port system (T. E. Notteboom & Rodrigue, 2005).

The formation of port region was also acknowledged by Martín-Alcalde et al. (2016) in their study of evolving roles of ports in the globalized world. The authors defined a port region as a "port system or a system of two or more ports located in proximity within a given area". The Hamburg-Le Havre range or Northern Europe, where the Port of Rotterdam is included, could be considered a port region. Besides geographical proximity, functional interdependence can be seen in this range since both sea and land services are shared (Martín-Alcalde et al., 2016). Port regions can vary in function and importance with respect to the traffic specialization and the continental context in which they play. Eight types of port regions were identified by Ducruet and Notteboom (2012). One being the "Metropolitan" typology, where port regions, such as the Hamburg-Le Havre range, are considered to be "richer, more densely populated and more service-oriented with lesser production activities, but handling more general cargo".

Again, with the exception of the paper by Aroca and Pruñonosa (2018), **no publication has been found relating the Physical Internet and the role or evolution of maritime ports**. For that reason, a particularization of the main PI characteristics to the role and evolution of maritime ports in freight transport systems is also justified. This will be further outlined in Section 3.2.

1.3.3. Scenario Analysis

Predicting the future accurately is a challenging task. Nevertheless, exploring the future is extremely relevant because "most of our actions are aimed at what lies ahead" (Enserink et al., 2010). This topic was already briefly introduced in Section 1.2, and when looking into the literature, there are varying definitions of the term scenarios. From the one described already by Hammond (1998), in Section 1.2, to the work of Van Notten (2006), who defined scenarios as "consistent and coherent descriptions of alternative hypothetical futures that reflect different perspectives on past, present, and future developments, which can serve as a basis for action". These descriptions can be drawn on the basis of questions. According to Börjeson et al. (2006), three different types of scenarios can be distinguished:

- **Predictive.** The aim of predictive scenarios is to make an attempt to predict what is going to happen in the future. In other words, these type of scenarios try to answer the question "What will happen?".
- **Explorative.** The aim of the second type is to explore situations or developments that are regarded as possible to happen in a long-time horizon. Hence, the goal is to answer the question "What can happen?".

- **Normative.** In normative scenarios. the study has explicitly normative starting points and the focus of interest is on certain future situations and how these could be realized. Therefore, normative scenarios give an answer to the question "How can a specific target be reached?".

In a similar fashion, Van Notten (2006) distinguished between normative and descriptive scenarios. The difference here lays in the aim to reach a particular point in the future (normative) or to simply outline possible futures without indications of desirability (descriptive). According to this author, scenarios can also be regarded as complex or simple with respect to their scope (i.e. set of external trends considered). It must be noted in this sense that the term "simple" does not necessarily mean "poor quality". In fact, "excessive complexity" can often lead to incoherent descriptions of the future, detached with the base or current situation.

To construct scenarios, qualitative or quantitative inputs can be used (Van Notten, 2006). The former is appropriate for high levels of uncertainty, where relevant information cannot be quantified. In this case, participatory approaches, such as the use of workshops, surveys or Delphi methods with experts are often used [see Enserink et al. (2010) or Börjeson et al. (2006)]. Whenever information can be quantified, computer models such as scenario discovery can be used (Halim et al., 2016).

The use of scenarios as a basis for strategic decision making is not new. The Dutch/British company Shell has been working on oil forecasts since the 1970s, which allowed them to adapt better to sudden fluctuations (Schoemaker et al., 1995). Global scenarios were also presented in 1999 by the Dutch Bureau for Economic Policy Analysis, by means of an economic forecast model[6]. In the field of logistics, many actors are trying to predict what can possibly happen so that they remain competitive in the market. For instance, based on input from surveys, interviews and workshops with experts, both internally and externally, the German company DHL elaborated a comprehensive scenario study about the future of logistics for 2050[7]. The examples already mentioned by the Port of Rotterdam in Section 1.2.1 prove the importance of the use of scenarios.

Examples of scenario discovery within the field of transport and logistics can also be found in the academic world. Halim et al. (2016) used an exploratory modeling approach to study future scenarios for the global container network. Participatory approaches are also widely used in transport scenario studies, with the Delphi technique as a common method for developing scenarios (Melander, 2018). For example, Cooper (1994) elaborated Delphi-based scenarios for the logistics futures in Europe, with over 200 experts from six different countries. Using a similar methodology, Piecyk and McKinnon (2010) elaborated three scenarios to assess the carbon footprint of freight transport in the UK for 2020. Gracht and Darkow (2010) used an extensive Delphi-based scenario study on the future of 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 [see Tolley et al. (2001); Tapio (2002); Shiftan et al. (2003); Mason and Alamdari (2007); Schuckmann et al. (2012); Tuominen et al. (2014); Liimatainen et al. (2014)].

As already expected, **no scenario studies have been found regarding the development of the Physical Internet**. Given the already mentioned interest of the Port Authority of Rotterdam, it is justified to elaborate scenarios for the development of the PI to assess how it influences the evolution of ports. The suitable type of scenario and methodology to work on will be explained in Section 2.3, and Chapter 4 will fully elaborate on the scenario outcomes.

[6] see WORLDSCAN.

[7] See Delivering Tomorrow, a scenario study by DHL for future logistics 2050.

1.4. Research Gap

As can be seen from Section 1.3, the PI concept is still in its early stages and a lot of questions still need to be answered before this paradigm can ever become a reality. Especially from the maritime perspective, where the future of freight transport systems on a PI context have remained unexplored. Therefore, the following research gap can be formulated:

Current literature does not provide insights into the way possible future developments of the Physical Internet can influence the evolution of maritime ports

This is rooted to a lack of a characterization that can show the interconnections between both the PI and maritime ports, showing how the development of the former can affect the evolution of the later towards "PI Ports". As a result, port authorities do not have the necessary knowledge to effectively anticipate, with strategic decisions, to the way global maritime freight systems can develop in the context of the PI.

1.5. Research Objective and Scope

Given the previous identified gap, the aim of this research is formulated as follows:

Generate contextual scenarios that influence the development of a port into a PI port so that Port Authorities can consider such influence in their strategic policies and therefore adapt accordingly.

To fulfill this objective, first a general characterization of the Physical Internet, followed by the way it affects the evolution of ports, should be presented. From here, scenarios on the evolution of the main PI characteristics, which influence the development of ports, would be generated. The Port Authority of Rotterdam, as the problem owner of this research, could use in later stages the findings of this research as a means to (1) quantify the impacts on the most relevant scenarios, and (2) to decide on possible strategic roadmaps to adapt to possible outcomes of the future.

1.6. Research Questions

As outlined above, the thesis aims to fill in an important gap by characterizing the Physical Internet and its impact on ports and ultimately generating scenarios for the development of the relevant PI characteristics that in turn affect the evolution of ports. Hence, the main research question (MRQ) is formulated as follows:

What are the scenarios for the development of maritime ports under the evolution of the Physical Internet?

In order to answer the main research question, the research is broken down into the following subquestions:

1. *What are the main PI characteristics?*
2. *How do the main PI characteristics influence the evolution of maritime ports?*
3. *What are the main external factors affecting the PI characteristics and how?*
4. *How do maritime ports evolve for each scenario?*

1.7. Thesis Outline

The remaining of the thesis will be organized as follows. Chapter 2 outlines the methodology to be used throughout the report. Chapter 3 elaborates on the main PI characteristics and constructs a framework which shows the evolution of these and how they influence the development of a port towards a PI Port. Chapter 4 elaborates contextual scenarios which can be used as input, together with the PI Port framework from the previous chapter, as input to generate the evolution path of the different PI characteristics per scenario, and eventually the evolution of the port. Chapters 5 and 6 finish the report by outlining, respectively, the main conclusions and reflections on the methodology, as well as on the outcomes. Table 1.1 summarizes the thesis outline:

Table 1.1: Chapter outline.

Chapter	Title	Sub-research question
1	Introduction	-
2	Methodology	-
3	The evolution path towards the PI Port	
3.1	PI Characteristics	1
3.2	PI Port framework	2
4	Scenarios	3 & 4
5	Conclusion	-
6	Reflection of the thesis	-

2
Methodology

This chapter outlines the scientific approach taken to answer the main (sub-)research question(s) proposed in this research. On a first stage, based on literature review and interviews with experts, the main PI characteristics will be outlined. This will be particularized for the context of maritime ports, were an evolution path of the port as a function of those PI characteristics will be proposed. A second stage will consist of the generation of explorative scenarios and, together with the framework of the previous stage, will be used as input for a Delphi survey with expertise, both from academia and industry, in the field of PI, ports, transport and logistics. Experts will select, for each given contextual scenario, how the different PI characteristics evolve. Lastly, the author will derive how these characteristics, for each scenario, influence the evolution path of a port towards a PI port based on the framework from the first stage.

2.1. Literature review

A literature review is a systematic method to identify and synthesise an existing body of research (Melander, 2018). It can be considered as the backbone of almost every academic work (Wilding et al., 2012). Chapter 1 identified the research gap and a need for a literature review to come up with the general key characteristics of the PI concept, and how these affect the development of maritime ports. Chapter 3 elaborates on the literature review.

2.1.1. PI literature selection criteria

Considering a concept that was scientifically introduced for the first time in 2009 (Montreuil, 2009), the current state-of-the-art regarding the PI literature is relatively limited. Nevertheless, as suggested by Treiblmaier et al. (2016), the PI literature has been constantly growing in the past years.

For this thesis, the sources of information will come from academic papers, conference proceedings, lectures or seminars published online (i.e., Physical Internet Center), and white papers. Only publications in English are considered, and master theses are excluded. Electronic databases for the search will be Google Scholar, in combination with the digital library of the TU Delft. Considering the scope of this research, for the academic papers, the search string "Physical Internet" will be used to identify relevant studies. Furthermore, only published papers prior to March of 2019 will be considered. Abstracts will be read to make a content check, and the selected publications will be categorized according to the methodology they applied. Since the purpose of this thesis is not to further build on the definition of PI or the research agenda, but rather to take the core findings from the existing knowledge to date, the papers which used the conceptual and theoretical, survey, or literature review as the main methodologies will be thoroughly studied. Once the contributions of all publications are discussed, core characteristics are identified through a counting technique.

It is important to note that some of the publications considered in the literature review have already been studied in the research context from Chapter 1. For validation purposes, the chosen publications from the literature review will be compared with those of Sternberg and Norrman (2017), who conducted a systematic literature review of the PI, to ensure that the most relevant sources were included in the entire PI literature review of this thesis.

2.1.2. Port literature selection criteria

According to Bichou and Gray (2005), which is the most cited paper found from Section 1.3.2, port literature has conceptualized port systems from different disciplinary levels without producing a comprehensive and structured discipline. Furthermore, the body of research in the field of ports is much larger than the young concept of the PI. Woo et al. (2011), which has been cited 136 times on Google Scholar, analyzed a total of 840 publications that ranged between the 1980s and the 2000s, which gives an orientation about the size and complexity of this field.

Albeit accepting that important contributions might be overlooked, it is not within the scope of this thesis to make a complete review of the existing port literature, which would make up to a full research project on its own. For that reason, the author considers the research context given in Section 1.3.2 to provide enough body of literature. This will be further complemented with company reports or articles within the field of maritime ports.

Except for the time period considered, these publications already followed a similar filtering approach than with the PI literature: they were in English; the main search engines were Google Scholar in combination with the digital library of the TU Delft; and master theses were excluded as primary source.

2.2. Expert Interviews

Direct consultation with experts about a certain topic can be considered a good way to gather information (Enserink et al., 2010). Experts knowledge will mainly complement the findings from the literature review and contribute to more robust characteristics of the PI. Moreover, they will also provide their opinion on what they consider to be important contextual factors for the development of the PI. Given the qualitative nature of the exercise around a young concept, the interviews will follow an unstructured format to allow the experts to freely give their opinion without any constraint or bias from the interviewers (Ratcliffe, 2002). In order to consider a potential candidate as an "expert" Enserink et al. (2010) recommends to check the following criteria:

- **Has substantial knowledge of a certain field.** Considering that the PI is an early concept, any of the following, or a combination of all of them, will be sufficient to consider someone as a "PI expert":
  1. Has published papers or conducted academic lectures related to the Physical Internet, or is about to.
  2. Has participated in events related to the Physical Internet, such as workshops or the "International Physical Internet Conference" (IPIC).
  3. Is or has supervised academic projects about the Physical Internet.
- **Is not afraid to deal with the uncertainty** and to explore the boundaries of his or her area of expertise, and **has the power of imagination.**

For this part, the expert selection criteria will be focused on the first point, that is, the "substantial knowledge of a certain field". This means targeting people who are openly active in the field of PI (published papers, conducted or assisted to several workshops,..), so that their contributions from the interviews can help reporting solid characteristics of the PI, which will be outlined in Chapter 3.

2.3. Scenario development

As already suggested by Börjeson et al. (2006), there are different types of scenarios: predictive, explorative and normative. In the context of this research, the purpose is to explore situations or developments that are regarded as possible to happen over a long-term horizon from a variety of perspectives. Therefore, the explorative scenarios are considered a suitable fit for this research. These are what Enserink et al. (2010) refers to as "contextual scenarios", which "provide images of possible future environments of the system to be taken into account [...]. These scenarios focus on the environment that cannot be influenced by the policymaker", which in this case is the Port Authority of Rotterdam. Given the qualitative nature of the exercise, with high levels of uncertainty, participatory approaches, such as workshops or Delphi studies can be suitable to explore these scenarios. Nevertheless, such methods are time-consuming and rely extensively on the input of experts. Considering that a Delphi will be already needed regarding the generation of "PI scenarios", which feed on the resulting explorative or contextual scenarios, a scenario logic approach will be used instead. The guidelines from Enserink et al. (2010) are suitable in this regard, which distinguish between the external or contextual factors, on the one hand, and the "system" that is being influenced, on the other hand. This framework thus allows to merge two stages of the thesis into one in a timely effective manner, and for that reason it is considered as a valid approach. Yet because this methodology is mainly tailored to validate policies, the steps for the scenario development from Enserink et al. (2010) will be adapted to this research.

Contextual factors (CF), defined as "variables that influence the development of the system but that cannot be influenced by the problem owners themselves" (Enserink et al., 2010), will be presented. This will be done by means of desk research, including academic publications as well as future trends in transport from companies and institutions, the previous aforementioned interviews and brainstorming sessions, also considered a "good instrument to generate factors" (Enserink et al., 2010). The "system" in this thesis is the resulting PI Port framework which will be outlined in Chapter 3, and the "problem owner" is the Port of Rotterdam. The contextual factors will be determined based on literature study (academic or reports), interviews with experts or brainstorming. The PESTEL framework (political, economic, societal, technological, environmental and legal)[1] framework is not considered strictly with the purpose to avoid rigidity and isolate a contextual factor to one particular PESTEL dimension only (Burt et al., 2006). This is done at the cost of potentially encountering strong inter-dependencies (non-orthogonality) of the driving forces.

In a next step, the contextual factors are clustered into different driving forces (DF) that determine the development of the factors from the previous step. These can be identified through brainstorming, causal maps or logic reasoning. Only the relevant driving forces will be considered for the next step, based on (1) the level of uncertainty, and (2) the impact these have on the "system" (Enserink et al., 2010), which will be the resulting framework from the literature review and interviews with experts depicted in previous Section 2.1 and Section 2.2.

Once the most relevant driving forces are identified, the "scenario logic" can be outlined. Each scenario results from a combination of the selected driving forces. Splitting the development of the driving force into 2 opposing directions [i.e. "high" and "low" or (+) and (-)], the number of scenarios will be 2 to the power of the number of selected relevant driving forces. Accounting for all the uncertainties within the global logistics system could lead to generating a massive number of scenarios (Halim et al., 2016). Nevertheless, since the scenarios will be used as input for a Delphi study, where fatigue plays an important role [see Section 2.4], the number of scenarios to be provided as input should be limited. Bradfield et al. (2005) recommends a final set of 3 to 6 scenarios. Moreover, from the literature review from Melander (2018) on scenario development in transport studies through a Delphi technique, the article with the largest number of scenarios was from Tuominen et

[1] The PESTEL framework can be considered a "mnemonic used in strategic management to group macro-environment factors to help strategists look for sources of general opportunity and risks", see Issa et al. (2010).

al. (2014), which generated 8 visions of the future. Based on these, between 2 to 3 driving forces, to span between 4 and 8 scenarios, will be finally selected. The generation of explorative (or contextual) scenarios will be presented in detail in Chapter 4.

2.4. Delphi

Developed at the RAND Corporation around the late 1950s (Dalkey & Helmer, 1963), the Delphi technique is a "method for the systematic solicitation and collation of informed judgements on a particular topic" (Turoff, 1970). Experts' opinion are suggested as the most reliable element available when facing an uncertain future (Durance & Godet, 2010). The main advantage of the Delphi approach is that (large) groups of experts which are located geographically apart can be involved and express their opinions anonymously. This anonymity also allows experts to change their mind in the course of the entire process without having to publicly announce it. For these reasons, the Delphi method has become one of the most widely accepted research methods used for future oriented research (Gnatzy et al., 2011). The number and different types of Delphi has grown, from the traditional method to the roundless Real Time Delphi (Melander, 2018). In this research, the Delphi process employed is based on the classic procedure, which is among the most approved variants of the Delphi (Gracht & Darkow, 2010).

For the case of this thesis, future explorative or contextual scenarios are not the outcome of the Delphi, as it is usually the case from literature (Melander, 2018). Instead, they are used as input, together with the PI Port framework or "system", to translate those explorative scenarios, through the Delphi tool, into what will be referred to here as "PI scenarios". This is outlined in detail in Chapter 4. The steps proposed for the Delphi study, which will be subject to reflection by the author in Section 6.1.4, are the following (Enserink et al., 2010):

1. Define and clarify the topic on which expert opinions is required. The formulation of the problem needs to be clear so that the experts make a similar interpretation.
2. Identification and selection of the experts, based on the guidelines proposed by Enserink et al. (2010), which suggests a size of panellists of about 12 members to provide valid outcomes. According to Mitchell (1991), the size of the panel "may be as large as time and money considerations will permit, but should not be less than eight to ten members". Accepting both statements, the Delphi study in this thesis aims for at least 12 panel responses per round. Potential panellists will be identified from online publications and workshops related to the PI. it is assumed that having knowledge in the PI, which entails transport and logistics in general, is enough to consider a candidate as knowledgeable in ports. Considering the risk of low response rate, this will be done to give room for more responses.
3. Drafting and mailing of questions for the first round. For clarification from the first point, they will be attached in the e-mail with a summary of this research and its purpose.
4. Answering and returning of the first round by the participants.
5. Analyzing and summarizing of the answers by the author of this thesis.
6. Drafting and sending of questionnaires for the second round, where participants receive a summary of the results from the first round together with a request to adjust their answers provided the new updated information. It is important to note that there is a risk of consensus towards more than one point (Hsu & Sandford, 2007). For this reason, albeit being the use of measures of central tendency (i.e. means, median, mode) or level of dispersion (i.e. standard deviation, IQR) favorable for Delphi surveys with scales delineated at equal intervals (Hasson et al., 2000), presenting these to the participants between rounds might be misleading. In this sense, presenting where the percentage of votes fell in each possible scale can give the experts a broader view.
7. Answering and returning of the second round by the participants.

8. Analyzing and summarizing of the answers by the author of this thesis. The decision to continue with more rounds depends on the degree of convergence in opinions that has occurred.

Including the selection of experts, the time window for panellists to fill in the questionnaire, and the processing between and after rounds can take several weeks. For that reason, proper scheduling and administration is needed. From literature, a minimum of 45 days for the entire study is recommended (Hsu & Sandford, 2007).

The questions can be structured by following an if-then rule. This is a common form of knowledge representation used in expert systems (Sasikumar et al., 2007). A rule means a structure which has an *IF* component and a *THEN* component. By applying this format to the Delphi, all the possible combinations of the selected driving forces (*IF*) can be outlined to the experts in an structured way, which can in turn provide their opinion (*THEN*). This is depicted in Table 2.1. For each scenario, in this example for 8 scenarios (3 driving forces), the experts would be shown an image of the future in which the selected driving forces have developed in a particular way (input), and they would be asked to give their opinion (output) about how the different PI characteristics (PI_1, PI_2, ...), which are developed in Chapter 3, evolve.

Table 2.1: Proposed structure for the Delphi questionnaire.

input for panellists		**output from panellists**	
IF	**Contextual Scenario**	**THEN**	**PI Scenario**
DF_1 is HIGH and DF_2 is HIGH and DF_3 is HIGH	1	PI_1 is... and PI_2 is... and PI_3 is...	1
DF_1 is HIGH and DF_2 is HIGH and DF_3 is LOW	2	PI_1 is... and PI_2 is... and PI_3 is...	2
DF_1 is HIGH and DF_2 is LOW and DF_3 is LOW	3	PI_1 is... and PI_2 is... and PI_3 is...	3
DF_1 is LOW and DF_2 is LOW and DF_3 is LOW	4	PI_1 is... and PI_2 is... and PI_3 is...	4
DF_1 is LOW and DF_2 is LOW and DF_3 is HIGH	5	PI_1 is... and PI_2 is... and PI_3 is...	5
DF_1 is LOW and DF_2 is HIGH and DF_3 is HIGH	6	PI_1 is... and PI_2 is... and PI_3 is...	6
DF_1 is HIGH and DF_2 is LOW and DF_3 is HIGH	7	PI_1 is... and PI_2 is... and PI_3 is...	7
DF_1 is LOW and DF_2 is HIGH and DF_3 is LOW	8	PI_1 is... and PI_2 is... and PI_3 is...	8

One of the main disadvantages in Delphi studies is the difficulty to keep respondents motivated during consecutive rounds. Low response or non-response can become a common problem [see Hsu and Sandford (2007); Gracht and Darkow (2010) or Spickermann et al. (2014)], mainly due to (1) the excessive length of questionnaires, and (2) an excessive number of rounds. Therefore, for practical reasons, the author of this thesis aims for no more than two rounds in total. Moreover, as it was already mentioned, the number of scenarios to be provided as input will be limited to no more than 8. Also, the questionnaire will be designed in such a way that it can be completed in a reasonable period of time, which the author considered to be less than 30 minutes per round. With this, fatigue among panellists can be kept as low as possible.

Consensus criteria

Delphi studies typically seek to reach consensus among the panellists [see Hsu and Sandford (2007) or Durance and Godet (2010)]. Nevertheless, the aim for consensus can hinder innovative or radical ideas, as pointed out by Melander (2018). The particular Delphi study presented in this thesis is structured in such a way that it does not allow for radical outcomes outside the possibilities to choose from (the PI characteristics presented to them) on a categorical scale, as it could potentially be the case of a Delphi to generate explorative scenarios. For this reason, the aim for consensus, albeit not being the ultimate goal, is desired in this thesis.

The criteria to define and determine consensus in a Delphi study is subject to interpretation (Hsu & Sandford, 2007). Some academics suggest that consensus is calculated by using interquartile deviations (IQDs), which represent the distance between the 25th percentile and the 75th percentile values in opinions (De Vet et al., 2004). The lower the IQR, preferably below 2 on a seven point Likert-type scale, the larger the consensus (Gracht & Darkow, 2010). An IQR ≤ 1 can be considered as good consensus on a seven-point scale, since it means that more than 50% of all opinions fall within one point on the scale (De Vet et al., 2004).

Other criterion suggest to define a percentage of votes to fall within a prescribed range (Miller, 2006). From some scholars, consensus is reached when 80 percent of subjects' votes fall within two categories on a seven-point scale (Hsu & Sandford, 2007). On the other hand, instead of using percentage measures, Turoff (1977) proposed to measure the stability of subject's responses in successive iterations.

Considering that Chapter 3 generates PI Port framework which evolves on a five-point scale, the consensus rule of IQR ≤ 1 from De Vet et al. (2004) is no longer enough. Moreover, as will be explained in Section 4.4.3, the limitations of the chosen tool does not allow to check consistency of the subject's responses, and the difference in the number of panellists between rounds could distort the results. Considering the previous, the following rule is proposed:

if IQR > 1, then no consensus
if IQR ≤ 1, then:

if % votes at mode < 50, then no consensus

if % votes at mode ≥ 50, then consensus

By considering this two-step approach, it would be assured that more than half of the votes fall within one category (mode), and the breadth of opinions between the 25 percentile and the 75 percentile fall next to the mode, never further than by one interval unit on a 5-point scale. When these two prerequisites are met, then consensus is reached. Section 4.4.4 presents the results of the Delphi survey, outlining the changes in consensus based on the criteria explained above.

2.5. Thesis approach

Considering the previous sections, the entire approach taken for this thesis is divided into two blocks which are used as input for the Delphi. The first part is the PI Port framework or "system", which is fully outlined in Chapter 3. The second part consists on the generation of contextual scenarios. Contextual factors are identified and then clustered into driving forces. Only those driving forces which are "relevant" are further considered, and their different combinations form the basis for the "scenario logic". The scenario logic, together with the framework from the first part, are then used as input for a Delphi survey. In each of the rounds, experts determine how each contextual scenario impact the development of the PI characteristics, which translate to a particular PI scenario where the evolution path of the port towards a PI port is outlined.

Figure 2.1 summarizes the entire approach taken for this thesis, as well as the techniques used for each part, the chapters they belong to, and the sub-research questions (SRQ) they answer.

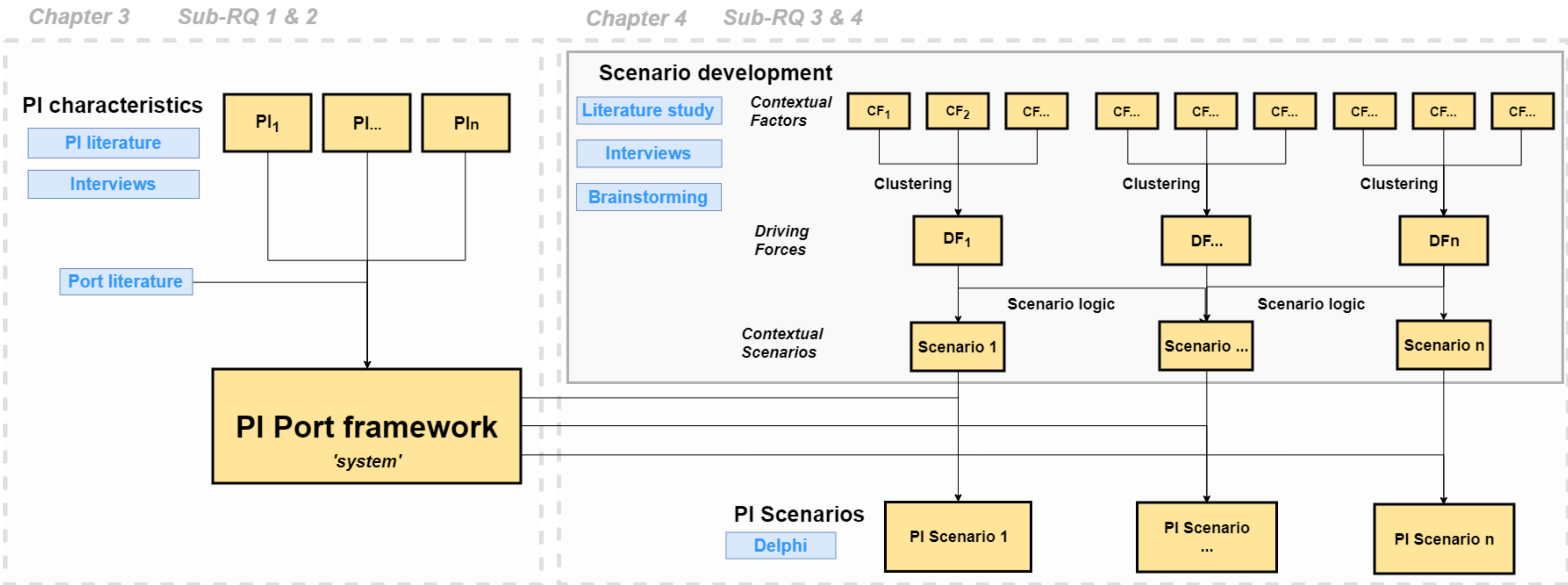


Figure 2.1: Overview of the approach taken for this thesis.

3

The evolution path towards the PI Port

As already briefly discussed, the PI concept is still in an infant stage (van Heeswijk et al., 2019). Studying its influence on maritime ports requires first a deep understanding about what the topic entails. Section 3.1 outlines the main PI characteristics based on an in-depth literature review and interviews with experts in the field of PI. The PI characteristics are then particularized to the context of maritime ports as nodes in freight transport systems, and ultimately a framework which shows the evolution of a port towards a PI Port as a function of the PI characteristics is outlined in Section 3.2.2. This is done in cooperation with MSc candidate Jeff Voster, who is also conducting research on the PI in the context of maritime ports, with a focus on developing a policy roadmap for the Port of Rotterdam. The resulting framework will then be used as input for a Delphi study, which is further explained in Chapter 4.

3.1. PI Characteristics

This section deals with the main characteristics of the Physical Internet. Section 3.1.1 outlines and discusses the selected publications within the PI, while section 3.1.2 presents the outcomes from the interviews with experts. Based on these two, the main PI characteristics are proposed.

3.1.1. Literature Review

From the literature review, a total of 40 academic papers that ranged from 2010 up to 2018 were reviewed. A lecture conducted by Montreuil (2019), which introduces the Physical Internet, has also been found and considered as relevant. Therefore, 41 publications were studied in total. It must be noted that all the papers which used more than one methodology (i.e., conceptual and simulation) were clustered into a multimethod group. Two opposite trends in the literature can be distinguished among the time period considered: the decreasing body of papers using purely conceptual methodologies against the increasing amount of publications using systematic literature approaches. From 2010 to 2012, the conceptual methodology was the dominant approach, where the core foundations and elements of the Physical Internet were outlined, such as in B. Montreuil (2011), B. Montreuil et al. (2010), or B. Montreuil, Meller, and Ballot (2012). Only at the end of this time period, other methodologies, such as simulation or modelling, tried to find the potential benefits of PI-enabled logistics systems defined in the conceptual studies, with E. Ballot, Gobet, and Montreuil (2012) or Sarraj et al. (2014) among the most cited publications. In the last years of the time period considered, critical literature reviews appeared to be the most used methodology, where papers, such as in Sternberg and Norrman (2017), tried to bring the body of knowledge created previously and set robust research agendas for the future. Table 3.1 summarizes the publications selected, as well as their main methodology applied.

Table 3.1: Research methods applied.

Main methods	Number of Publications	Publications
Conceptual	14	Montreuil et al. (2010); Montreuil (2011); Montreuil, Ballot and Fontane (2012); Montreuil, Meller and Ballot (2012); Montreuil, Rouges, Cimon and Poulin (2012); Cimon (2014); Oktaei et al. (2014); Rouges and Montreuil (2014); Tavasszy et al. (2015); Colin et al. (2016); Montreuil (2016); Crainic and Montreuil (2016); Tavasszy (2018); Montreuil (2019)
Simulation	7	Ballot, Gobet and Montreuil (2012); Sarraj et al. (2012), Pan and Ballot (2015); Pan et al. (2015); Sallez et al. (2015); Sallez et al. (2016); Krommenacker et al. (2016)
Literature review	6	Treiblmaier et al. (2016); Sternberg et al. (2017); Pan et al. (2017); Zijm and Klumpp (2017); Domanski et al. (2018); Ambra et al. (2018)
Mathematical model	5	Sohrabi and Montreuil (2011); Lin et al. (2014); Montreuil et al. (2014); Quiao, Pan and Ballot (2016); Venkaradri et al. (2016)
Conceptual design	3	Ballot et al. (2012); Meller et al. (2012); Montreuil et al. (2013)
Multimethod	3	Sarraj et al. (2014); Ballot et al. (2014); Aroca et al. (2018)
Case study	1	Ballot and Fontane (2010)
Interviews	1	Simmer et al. (2017)
Product design	1	Landschutzer et al. (2015)
Total	41	

For validation purposes, the chosen publications were compared with those from Sternberg and Norrman (2017), who selected a total of 46 publications by using a systematic approach. Overall, 26 were considered in both reviews, with a complete match in those where the main methodology was conceptual. In this category, the most cited publication, which presented the domain of PI from a scientific point of view (B. Montreuil, 2011), was included in both reviews. An interesting finding is that two of the most cited publications in the domain of PI [see B. Montreuil et al. (2010) and B. Montreuil, Meller, and Ballot (2012)], from which most of the other publications relied on as starting point of their study, were excluded in the systematic research conducted by Sternberg and Norrman (2017). When looking into the systematic review carried out by Treiblmaier et al. (2016), it was found that only B. Montreuil et al. (2010) was used to derive what they considered to be a "PI component", namely "open transit centers". The other publication was merely mentioned throughout the paper, without using it to derive any "required component".

Another finding is that a solid definition of the PI is not fully clear when one dives into the literature, suggesting that research on the concept itself is still in its infancy (van Heeswijk et al., 2019). According to Pan et al. (2015), the PI is an "innovative organization of supply chains". Venkatadri et al. (2016) defined PI as a "contemporary conceptualization of a highly modular logistics network that mimics the routing of packets over a network of hubs in the virtual Internet". Likewise, many academics simply mention what they consider to be the core characteristics of PI, leaving the explanation behind such statements overlooked. For instance, Venkatadri et al. (2016) defined the two main characteristics of PI as the following: (1) container modularization through the use of PI containers, and (2) their routing over a global transportation network through specialized intermodal cross-dock facilities (PI hubs). Despite differences in the level of abstraction on the concept, there appears to be some consensus around the first formal definition, introduced by B. Montreuil, Meller, and Ballot (2012) which was then quoted by 13 of the 41 publications listed previously in Table 3.1:

The Physical Internet is an open global logistics system founded on physical, digital and operational interconnectivity through encapsulation, interfaces and protocols.

A later formal statement has been found (Montreuil, 2019), which merely builds upon the previous one:

A hyperconnected global logistics system enabling seamless open asset sharing and flow consolidation thrgouh standardized encapsulation, modularization, protocols and interfaces to improve the efficiency and sustainability of serving humanity's demand for physical objects.

Landschützer et al. (2015) gave a similar meaning to the PI, being a "global logistics system based on the interconnection of logistics networks by a standardized set of collaboration protocols, modular containers and smart interfaces for increased efficiency and sustainability". Despite the formal definition, which was shaped by exploiting the Digital Internet metaphor (Crainic & Montreuil, 2016), the first foundation of PI was formulated as "a mean to an end, and not an end by itself" (B. Montreuil, Meller, & Ballot, 2012).

While this can create confusion, it is reasonable to consider the previously mentioned formal definition as the *means to an end*, with the *means* being broken down into different characteristics or components. The *end*, in turn, is to "improve the way physical objects are moved, deployed, realised, supplied, designed and used" from an economical, environmental and societal perspective, as suggested by B. Montreuil (2011). This ultimate goal is indeed agreed upon the academia, being quoted on several of the publications reviewed, such as in Sternberg and Norrman (2017). By taking this approach, the PI characteristics to be derived from the literature review presented in this thesis can be seen as the *means* to the *end* mentioned by B. Montreuil, Meller, and Ballot (2012). From literature, and through a counting technique, the main characteristics that enable the overall vision of the Physical Internet seem to be: **(1) modularity, (2) encapsulation, (3) protocols, and (4) interfaces**.

Since experts are being consulted after the literature review in a Delphi study, the main characteristics need to be well differentiated and avoid any possible vague definition. The following paragraphs define and explain them in detail, as well as the sub-elements or sub-characteristics that may arise from them, and how they are interrelated.

Modularity

Modularity seems to be one of the core characteristics of the Physical Internet vision, as it was addressed, or at least mentioned, in 31 out of the 41 publications that comprised the PI literature review. E. Ballot et al. (2014) defined the system of modular containers as the primary fundamental component [...], not only to create a private space in a more open system, but also to standardize measuring flow, handling and therefore reducing its cost. Treiblmaier et al. (2016) also identified the modular containers as one of the main PI components. Likewise, Sternberg and Norrman (2017) stated that, just as in the Digital Internet, the concept relies heavily on modularity. In fact, the EU-funded Moduluscha project is currently designing standard container prototypes which can enhance interconnected logistics networks (Landschützer et al., 2015).

The main idea behind the Physical Internet is to move goods the same way the Digital Internet does with the movement of data. The DI deals with modular packets in which the information is encapsulated. In other words, the DI does not deal with the content information of a particular message directly, but rather with information on the dataflow that makes the routing possible via a protocol. Exploiting this analogy, physical goods are not directly manipulated by the PI but are encapsulated in standardized containers [see B. Montreuil et al. (2010), Landschützer et al. (2015) or Sallez et al. (2016)] which need a sound information system.

From the papers, *modularity* mainly refers to the so-called π-containers, which are the fundamental unit loads of the PI, designed to be delivered via an interconnected logistics networks (E. Ballot et al., 2014). To date, three categories of π-containers, in ascending size order, have been distinguished [see Krommenacker et al. (2016) or Montreuil (2019)]: packaging container (π-packs); handling container (π-boxes); and transport container (π-pods). These are meant to be easy to handle, store and transport, as well as smart and connected to each other so that the flow of information is possible and made transparent. Furthermore, these containers are meant to be eco-friendly, made out of reusable or recyclable materials and with a minimal footprint (Montreuil, 2019). Figure 3.1 summarizes the different categories, how they interrelate with each other and their main functionalities:

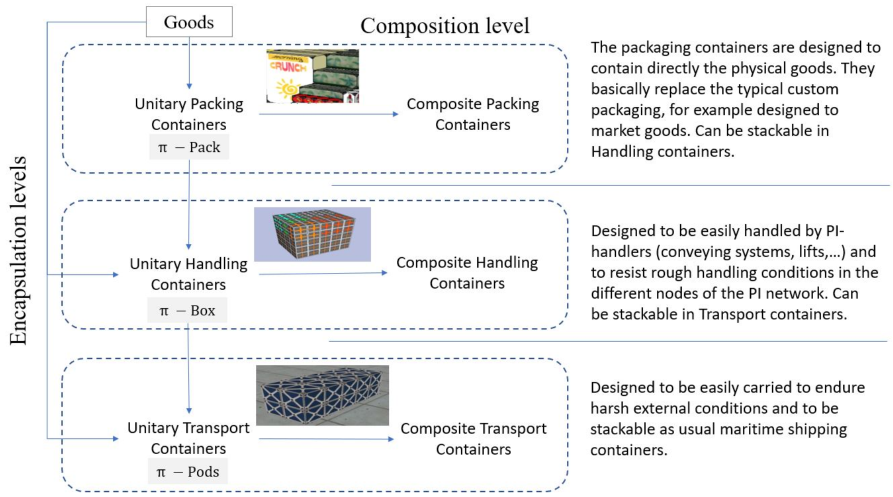


Figure 3.1: Three main categories of π-containers. Adapted from Krommenacker et al. (2016) and Montreuil (2019).

As can be seen in the figure above, each category can be successively encapsulated or stacked one within the other, following an analogy to the Russian doll concept. Furthermore, in a same horizontal category, the π-containers can be composed and interlocked to build "composite" π-containers for easier handling of transport (Sallez et al., 2016).

From the literature it seems that *modularity* is an important characteristic of the PI. Despite being out of scope of the present project, it must be noted that, as with the definition of PI itself, most of its characteristics are still at a research phase. As is often the case with bold new visions of future innovation in the transport industry, there is a "dearth of practical and empirically grounded experiences in the PI" (Pan et al., 2017). For the case of modular containers, only prototypes have been proposed and full consensus has still not been reached among academics and industry about their technical specifications. Therefore, these conceptual designs could change over the years as they interact with socio-technical regimes and other external factors, or even stagnate, as suggested by Geels (2002). Nevertheless, it is not within the scope of this thesis to propose a particular design of a container, but rather to accept that some academics consider it as an important characteristic of the Physical Internet.

Encapsulation

The term *encapsulation* appeared in 29 of the 41 publications. Yet, when diving into the literature, a lot of inconsistencies can be found, especially when trying to draw the line between this term and *modularity*. For instance, Treiblmaier et al. (2016) did not include encapsulation as a "component" of PI, whereas modularity was indeed part of it. Other authors did identify the "encapsulation of goods as a key principle of PI" (Landschützer et al., 2015), with the encapsulation being physically realized by containers.

Moreover, most of the quotations found on the literature were made to refer to the analogy between the Digital Internet and the Physical Internet, using the term *encapsulation* as a connector of both concepts. Oktaei et al. (2014) outlined the previous by suggesting that, in the Physical Internet, "products are transmitted through encapsulation in world-standard, modular, reusable, and smart π-containers, similarly as moving data through encapsulation in standard packets under TCP-IP protocols". This analogy has been pointed out in other publications [see for instance Sallez et al. (2015), Treiblmaier et al. (2016), or E. Ballot et al. (2014)].

Only in fewer papers was the term *encapsulation* addressed in more detail. Following a similar layered structuring of digital services and protocols which shape the DI, B. Montreuil, Ballot, and Fontane (2012) defined a 7-layer model, known as the Open Logistics Interconnection (OLI) model from which the interconnected logistics services proposed in the PI could function. One of the layers is the "Encapsulation layer", in which products are assigned to their π-containers. Colin et al. (2016) proposed a New Open Logistics Interconnection (NOLI) reference model, where the (de)-containerization of the Encapsulation Layer was moved to a the topmost "Product Layer". Table 3.2 summarizes the layers of the TCP/IP protocol of the Digital Internet and the two proposed models of the Physical Internet.

What can be concluded from literature is that both *modularity* and *encapsulation* go hand in hand. Goods are encapsulated in modular containers, these being currently investigated and tested. In fact, a causal relationship can be seen between the later and the former. Without modular containers, encapsulation of goods in the PI would not be possible [see Figure 3.1 above]. The major difference between both, by looking into part of the literature, is that by encapsulation, products are "assigned" to containers. This operation, however, needs a set of of standard protocols and interfaces so that the container assignment can be done, which shows the dependency with the other overall main characteristics. Therefore, from the literature review, the author proposes *encapsulation* to be merged within *modularity*.

Table 3.2: Layers of the TCP/IP OSI model, OLI model and NOLI model (Colin et al., 2016).

TCP/IP Layer Name (Internet)	**OSI reference Model Layer Name**	**OLI Layer Name (Montreuil et al.)**	**NOLI Layer Name (Colin et al.)**
Application	7. Application	7. Logistics Web	7. Product
	6. Presentation	6. Encapsulation	6. Container
	5. Session	5. Shipping	5. Order
Transport	4. Transport		4. Transport
Network	3. Network	4. Routing	3. Network
		3. Network	
Network Access	2. Data Link	2. Link	2. Link
Physical	1. Physical	1. Physical	1.Physical Handling

Interfaces

Mentioned in 29 publications, *interfaces* appeared as another main enabler in the formal sequential definitions [see B. Montreuil, Meller, and Ballot (2012) and Montreuil (2019)]. Nevertheless, different perspectives have been seen in the papers which addressed the term.

In their joint research, E. Ballot, Montreuil, and Thivierge (2012), Meller et al. (2012) and B. Montreuil et al. (2013) mentioned both "handling" and "digital" interfaces. These are needed, according to the authors, for reliability, security, transparency and quality of the product throughout the entire trip. Sarraj et al. (2014) referred to the "interfaces between the containers and the different means of transport and handling to carry out grouping and de-grouping". In fact, this research linked two of the main characteristics by stating that the resulting modular containers will consist of different "sizes, interfaces and functionalities". E. Ballot et al. (2014) also addressed both the handling and digital side of interfaces. Regarding the first one, the authors mentioned the twist-lock system standardized by ISO 1161 1984 as an example of a handling interface for maritime containers, which revolutionized global trade into what is known nowadays. In the PI level, the handling interfaces would serve a similar functionality between π-containers and vehicles, also known as π-movers according to B. Montreuil et al. (2010), yet going beyond and globally implementing them within and across all modalities.

The digital interfaces have also been addressed in the literature from different perspectives. Identifying the traceability of the π-containers as a source of new value-added services, Krommenacker et al. (2016) proposed, as a means for interconnectivity, wireless sensors to act as the interfaces between "management information system (or π-operators) and the composite container". In the interviews conducted by Simmer et al. (2017), the authors asked companies about what they considered to be the greatest "challenges for horizontal collaboration". The interfaces with customers from a digital perspective appeared to be one of the biggest bottlenecks, besides cultural barriers. A similar meaning was given by Rougès and Montreuil (2014), who used the term from a business perspective to refer to IT applications from which customer and business can interact. Rougès and Montreuil (2014) developed a typology of business models in the crowdsourcing industry, identifying the different interfaces used by companies, such as websites or mobile applications. Furthermore, B. Montreuil, Ballot, and Fontane (2012) proposed the Logistics Web layer in the OLI model [see Table 3.2] as the interface between the PI and the users of logistics services, where the traceability function described before is included. It provides the "functional and procedural means [...] to take dynamic decisions about product supply, realization, distribution an mobility through and open and global Logistics Web". Different levels of protocols and interfaces were identified by Crainic and Montreuil (2016): digital (data, transactions,...); physical (packaging, vehicles,...), operational (activities within facilities and the meeting of vehicles and facilities), and business models (contracts).

Some of the publications did not dive deep into the term [see Cimon (2014), Oktaei et al. (2014), Lin et al. (2014) or Landschützer et al. (2015)]. Both Treiblmaier et al. (2016) and Sternberg and Norrman (2017) quoted the main definition of PI, without giving further details. In the former, some of the "facilitators" of the "PI components" that came from the authors, however, are rooted in either handling interfaces (to create "effective cargo handling") or digital interfaces ("information sharing about delivery status"). Pan et al. (2015) defined an interconnected network of open π-hubs through "standardized interfaces and the goods are transported and stored through modularized and standardized smart containers". In the design of omnichannel interconnected business-to-consumer logistics, B. Montreuil (2016) identified "standard protocols and interfaces for seamless open asset sharing and consolidation across interconnected networks and nodes" as one of the key characteristics of the Physical Internet. Aroca and Pruñonosa (2018) referred to the gateways, major hubs such as mainports, to act as an "interface between regional and global trade".

In this research, *interfaces* refer to the connection between two elements, both from a physical (handling) or digital perspective. Important sub-characteristics appeared in the literature to be enabled by both the digital and the handling *interfaces*. One of them being *interconnectivity*. As suggested by E. Ballot et al. (2014), the connectivity of all "things" is enabled by equipping objects with interfaces that gives them the capacity to communicate with their immediate environment. It can also be inferred that *"collaboration"* can be enabled both by handling and digital interfaces. Sharing of resources needs to have standard ways of communication between all actors, from vehicles to nodes, as well as standardized handling interfaces which allow for horizontal synchronization of modes throughout the trip.

Protocols

The term *protocol* was used in 31 of the 40 publications from the literature review. E. Ballot et al. (2014) defined it as a "set of professional rules to be observed by each of the stakeholders in a network (handler, facilities, software agent, etc.)". Yet, the term has not been given a consistent definition throughout the literature.

As with *encapsulation*, the analogy in which a set of *protocols* are used in the DI environment could be replicated in the PI. Yet from literature an important difference between both worlds was identified. In the former, protocols refer to the internal communication between the different networks, but also to the management among them (Sarraj et al., 2014). The goal of the TCP/IP model (see Table 3.2) is to "provide a set of protocols that separates the needs of communication applications from the specificities of the real networks used to transmit the data" (Colin et al., 2016). A direct transposition of this definition cannot be done to the PI world, since the "physics of information and objects are too different" (E. Ballot et al., 2014). For instance, in the DI environment, routing protocols lose a significant amount of sent data, but is not considered a problem because digital artifacts can be resent almost at no cost. This is not the case for the routing of physical goods, where lost parcels could result in serious additional costs. Moreover, the time to send a data packet is extremely low when compared to the shipping of a good over a long distance, which can take several days.

A common application to the "set of rules" in the PI referred to the efficient transport of vehicles. For instance, Sarraj et al. (2014) outlined that routing protocols between nodes (π-hubs) may be useful to understand "flows and estimate their future state to prepare the routing". The authors designed a transportation protocol for an open and interconnected network. In their paper, they referred to "protocols" as the "functioning rules guiding operation" of an open and interconnected PI, similar to the definition described above. The research was focused on creating loading modular containers from orders, finding the best origin-destination path for these boxes within the PI network, while ensuring efficient consolidation in each vehicle throughout the trip. The algorithm-based protocol, which can also be referred to as an optimization problem, showed improved performance in terms of CO_2 emissions, cost or lead time. In a similar fashion, Sallez et al. (2015) pointed out that the degree of predictability will be very low in the context of the PI, with a limited time window to react. For that reason, the authors presented a reactive algorithm for the routing of containers in perturbed environments in a cross-dock. Again, the term *protocol* was referred to as the mathematical model. In line with this, Ambra et al. (2017) acknowledged the need for automated assets such as π-containers, π-conveyors or π-handlers to apply to quickly respond for unexpected events. Moreover, with the use of wireless sensors attached to the π-containers, Krommenacker et al. (2016) proposed a framework for the (de-)composition of π containers. The loading pattern followed a "neighbour discovery protocol", where real-time information exchange between containers and the management system (referred to as a π-operator) ensures efficient positioning of the boxes.

Apart from the purely routing perspective, a negotiation protocol was proposed by Oktaei et al. (2014) for the design of business models for transit centers, the most basic facilities of the PI environment. The negotiation protocol, named by the authors as a "π system", is a manager of the information shared and used by each entity. The system automatically monitors in real time the location and state of all actors involved, which for the case of a π-transit center could be π-trucks, π-trailers or neighboring π-hubs.

B. Montreuil, Meller, and Ballot (2012) proposed different levels of protocols to ensure a collaborative behaviour without the need to enter in current one-to-one cooperation agreements. According to the authors, basic protocols would be used to validate the integrity of π-containers flowing through the networks (or π-networks). On the other hand, high-level protocols would focus on the integrity and performance of the π-networks, routing of the π-containers or the management of the shipments. Likewise, in their joint research, E. Ballot, Montreuil, and Thivierge (2012), Meller et al.

(2012) and B. Montreuil et al. (2013) considered the "open standard set of collaborative and routing protocols" to be another enabling technology of PI. The authors suggested that the efficient routing of modular containers over a collaborative network can only be realized with a "standard set of routing and digital protocols". To achieve sharing of resources such as data or assets, Treiblmaier et al. (2016) concluded that a set of "common and universally agreed-upon standards and protocols are needed to facilitate horizontal and vertical cooperation between companies". The authors identified "open, shared and secure protocols" as an enabler of "seamless data exchange", considered a key component in their research. Similarly, Ambra et al. (2017) mentioned that "standard coordination protocols" should be first established to ensure shared and cooperative consumption of assets. Likewise, according to Sternberg and Norrman (2017), the PI builds on "horizontal collaboration, between decentralized public and private actors, using standard technical protocols". Zijm and Klumpp (2017) addressed the relationships between a competent workforce and the technological innovations, such as "automated decision protocols", which the Physical Internet concept depend on.

To conclude, in this research, standard *protocols* refer to the set of rules from which all actors operate and interact with each other. From algorithms for the routing of vehicles to the positioning of boxes or even agreements between two parties in the logistic network. As with *interfaces*, important characteristics that come from it in the literature were *collaboration* and *interconnectivity*. Although *automation* could be seen as an enabled characteristic of *protocols*, the literature does not draw a clear separation line here. Automated systems indeed consist of a set of standard protocols to perform dedicated activities in supply chains, from routing algorithms of a vehicle to the handling of automated equipment inside a hub, as suggested by L. Tavasszy (2018). Yet, interconnected actors such as vehicles could also automatically communicate with each other. Sharing of assets through collaboration could also be done without human intervention if proper standard protocols are in place.

Conclusion from the PI literature

In Chapter 1, the need for a review, the research context as well as the literature gaps and main (sub)research questions were formulated. Albeit these not only needed for PI itself but for the entire thesis, the first stage set out the path for a robust and thorough literature review. Publications were selected and categorized according to the applied methodology. Following the formal definition of the PI, the main characteristics were derived, through a counting technique, as the *means to an end*.

Some of these were further developed into more clear characteristics to be used for further stages in the thesis, where experts will have to provide their input based on these elements. The findings from the literature review presented here have been subject to discussion with MSc candidate Jeff Voster, who also came to the same conclusions through his literature review. From the 41 publications analyzed, and the follow-up discussion with the other mentioned student, the proposed characteristics are the following:

- **Modularity.** As already discussed, it seems to be one of the core characteristics of the Physical Internet. It encompasses not just the π-containers, but also the encapsulation of all types of goods in these boxes. These are transported and handled in π-vehicles and all sorts of tools which are equipped with handling *interfaces*. In order to encapsulate goods into boxes and stack these into composite containers, algorithms or *protocols* are followed.
- **Collaboration.** This component can take a broad definition, but from the literature the most important notion is the "sharing of resources and assets between the different players". Digital tools or *interfaces* can allow different carriers publish in real time their available capacity, therefore matching a particular demand 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 π-containers. From a business and legal perspective, dif-

ferent 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 seems to be the "connectedness of the different movers, containers, hubs and other players in the logistics network". That is, they can share information, communicate and make decisions automatically which 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 can help in such endeavor. An example could be the usage of passive RFID tags on π-containers to facilitate their traceability[1], where handling tools such as Cranes or Automated Guided Vehicles (AGV) follow a Dynamic Model Predictive Control (DMPC) as the main protocol[2].

Automation was identified in the literature as a potential characteristic. Nevertheless, a distinct line with the rest of the enablers, especially *interconnectivity*, was not fully clear. For that reason, this particular element is subject to discussion with the interviews with experts.

A final remark that could be extracted from the literature review is that a theoretical base for the development of the Physical Internet is lacking (Treiblmaier et al., 2016). B. Montreuil, Meller, and Ballot (2012) considered the PI as a "myriad of components that [...] through their well-designed relationships and interdependencies, the system (PI) as a whole could achieve its purpose completely". Yet those components might be subject to many changes and transitions depending on the socioeconomical or technological context.

3.1.2. Interviews with Experts

To complement the literature review, the found characteristics were subject to discussion with experts in the field of the Physical Internet. This was done through interviews conducted together by the author of this thesis and MSc candidate Jeff Voster. Due to availability, a total of 4 interviews were conducted, with people located in the Netherlands, Germany and the United States:

- Interview 1: Dr. N. Szirbik and Dr. G. van der Heide
- Interview 2: Prof. Dr. B. Montreuil
- Interview 3: Prof. Dr. L. tavasszy
- Interview 4: A. Nettsträter

For sufficient breadth of opinions, 8 to 12 experts are usually desired, as pointed out by Enserink et al. (2010). Yet, for this case, their relevance of work and contribution in both the academic and industry fields in the PI context made them however suitable experts. Moreover, some of them spoke on behalf of a community of experts in the field, both in the United States and Europe. For this reason, the opinions given are considered to be sufficient.

The interviews followed an unstructured format, to allow experts to freely express their opinions and avoid bias from the interviewers. The purpose was to ask them for feedback about the outcomes of the author from the literature review, and what they considered to be the main PI characteristics. The full discussion from each of the interviews can be found in the Appendix B. Furthermore, considering the unique opportunity to have a direct talk with experts in the field, both students took the chance to ask them about what they considered to be important "contextual factors" for the development of scenarios, which will be further used in Chapter 4. Several conclusions can be drawn from the interviews:

[1] Albeit being out of scope, the author of this thesis recommends Ahmad and Mohan (2014) or Lu et al. (2017) for more information about RFID technology.

[2] For more information on Multi-Agent control structures, see Negenborn et al. (2010).

- Each expert, with different backgrounds, has seen the Physical Internet from a different perspective, and yet they all came to valid and arguable conclusions of their vision of the PI. Instead of "characteristics", they referred to as "components", "building blocks" or "areas of interests".
- As already said, there was no rigid structure in the format of the interviews. This was done on purpose to avoid bias by the author of this thesis, stirring the discussion into a particular direction. In this way, the experts were given freedom to express their overall vision of the Physical Internet without constraints. Yet, because of this lack of structure, very limited time was left to discuss the contextual factors, which are used in Chapter 4. The experts did not have time to go through all the list provided to them, and instead they were asked to mention the factors they considered as relevant.
- There is a lack of consensus on what the PI characteristics are, as already identified by the author in the literature review. Many components or building blocks might have proven, in the context of the PI, to have a different meaning between the literature and the interviews. This could be troublesome for the Delphi from Chapter 4, where experts could have different interpretations of a particular term. This was the case, for example, with the term *collaboration* and *cooperation*. Whereas the European experts did not draw a clear line between both, the consulted expert in the United States, Prof. Montreuil, highlighted the important difference between both. Likewise, the second interviewed expert made a clear definition of the term "hyperconnectivity", which meant, according to him, "intense interconnectivity on multiple layers". On the other hand, the SENSE experts used a broad definition of "connectivity" instead, also considered as interconnectivity on multiple layers (digital, physical, etc.).
- The rigid approach taken in the literature review phase, based on a counting technique, proved to give an incomplete view of the Physical Internet. This rigidity was also applied with the term "characteristics", whereas the experts referred to "components", "building blocks" or even "areas of interest". The interviews helped envisioning a more general foundation of the Physical Internet.
- From the interviews, there seems to be a different research direction or agenda regarding the Physical Internet between two distinct geographical regions. This is reflected in the different dimensions or levels of abstraction in which the topic is being studied. On the one hand, academics located in the United States seem to be focused on Operational Research issues, such as the routing of π-containers, and at a broad Supply Chain Management level. The "Physical Internet Center", located in Georgia Tech University and led by Prof. Montreuil, can be considered the flagship institution in this regard. On the other hand, apart from the experts consulted in Groningen (The Netherlands), which have a focus on AI and agent-based modeling, somewhat similar to what is done across the ocean, the European experts seem to have a more pragmatic focus at a transport level. With the proposed roadmap in the ALICE project, more than 20 experts from different fields and backgrounds had to reach consensus on what they considered to be "areas of interest" in the PI and they way it could potentially evolve, known as "PI Generations".
- A final conclusion that could be extracted from the interviews is that *automation* seems to be an important element of the PI, yet still complementary to human labour in some parts of freight transport systems. For the case of ports, handling operations are already on their way towards high levels of automation, and with the PI this trend could be expected to continue.

3.1.3. Resulting PI Characteristics

Table 3.3 summarizes the different characteristics depicted by each expert [see Appendix B for the full discussions], as well as those derived from the literature review. It must be noted that the last two interviews were merged into one. The reason for this is that their own vision of the PI was used as input for the SENSE workshops, and the elements in the last column are a result of several brainstorming sessions which ended up with consensus around these. Therefore, they could be considered as a whole, representing the input of more than 20 "PI experts" located in Europe.

Table 3.3: Summary of the different PI characteristics from the literature review and the interviews with experts.

Literature Review	Interview 1	Interview 2	Interviews 3 & 4
Modularity	Modularity	Certified Open Logistics Service Providers	System Level Functionality
		Smart Data-Driven Analytics, Optimization & Simulation	
	Openness	Open Logistics Decisional & Transactional Platforms	Governance
Collaboration		Global Logistics Monitoring System	
		Certified Open Logistics Facilities and Ways	
	Automation	Standard Logistics Protocols	Network Services
Interconnectivity		Containerized Logistics Equipment and Technology	
	Decentralization	Unified Set of Standard Modular Logistics Containers	Nodes

For practical reasons, the terms "characteristics", "components" or "building blocks" are used indistinctly to refer to the first two sub-research questions of the thesis [see Section 1.6]. As already mentioned, the characteristics (or building blocks) derived in the literature review gave a limited picture of what the Physical Internet entails. With the input provided by the experts, a more general image of the PI could be drawn. It must be noted, however, that it is not the ultimate goal of this thesis to come up with a unified definition of the Physical Internet that everyone will agree upon. Instead, the purpose is to try to capture most of the relevant knowledge created in the topic, by breaking it down into different components or building blocks, which can be used as input for the Delphi survey.

Because of the different levels of abstraction used by the interviewed experts, their components have been clustered into distinct dimensions. These layers result from a generalization, or upscaling of the definitions given to the three characteristics derived from the literature review. Three layers are distinguished: (1) digital layer; (2) business and contractual layer; and (3) physical and operational layer.

Digital layer

The author of this thesis initially defined "interconnectivity" as "the connectedness of the different [...] players in the logistics network. That is, they can share information and communicate automatically with each other". This proved to give a rather incomplete view of the term "interconnectivity", as suggested by Prof. Montreuil, and for that reason a generalized digital layer is taken instead.

From the first interview, "decentralization" could be included in this first layer, since it was referred to as a new digital control architecture in which each individual actor could communicate and make decisions without the guidelines of a hierarchically superior entity. In this regard, "automation" would be clustered in a similar way. Yet this component also overlaps with the physical and operational layer, since through the aforementioned control architecture, decisions and operations are made throughout the network. From the second interview, "smart data driven analytics, optimization and simulation"; "decisional & transactional platforms"; and "monitoring system" are included in this general digital layer.

Physical and operational layer

"Modularity" took a broad definition from the literature review. This definition is expanded to not all the physical elements in the network, and also to how they physically operate. This way, considering the opinions from the experts, the choice to consider π-containers or current standard containers as loading units remains open.

In this layer, "containerized logistics equipment and technology", which could be automated or not, and the "unified set of standard modular logistics containers" are considered from the second interview. These overlap with the "modularity" component from the first interview. "Open facilities and nodes" are also included.

Business and contractual layer
"Collaboration" was initially defined as the "sharing of resources and assets between the different players". Renaming it to "cooperation", only the business and contractual dimensions are considered here. In this layer, "openness" is considered to have the best fit, since the use of the PI and all its advantages are not limited to the big players who are currently undergoing long-term alliances. From the second interview, "certified open logistics service providers" were merged into the business layer. Lastly, the "standard logistics protocols", which referred mainly to a new generation of rules fitted to allow for the cooperation of all players, was destined to this business and contractual layer.

Some of the blocks of the last interviewed experts, which can be regarded as the SENSE experts, have already a generalized overarching vision, where the different layers or dimensions converge. This is the case of the "Nodes", which can be considered physically as the hubs themselves, as well as the function they perform in the transport network from a contractual and digital perspective. The "network services" could be seen from an operational, digital and business perspective to allow for fast, reliable and resilient logistics services in the PI. Similarly, the "system level functionality" refers to the way the different actors function in freight transport systems, increasing in connectivity (from a digital, operational or business perspective) with the other players over the years. "Governance" has a business and contractual function mainly, and overlaps with the rest of the components within the business dimension (i.e. "standard logistics protocols"). Figure 3.2 summarizes the generalized characteristics of the Physical Internet based on the outcome from both the literature review and the interviews with experts.

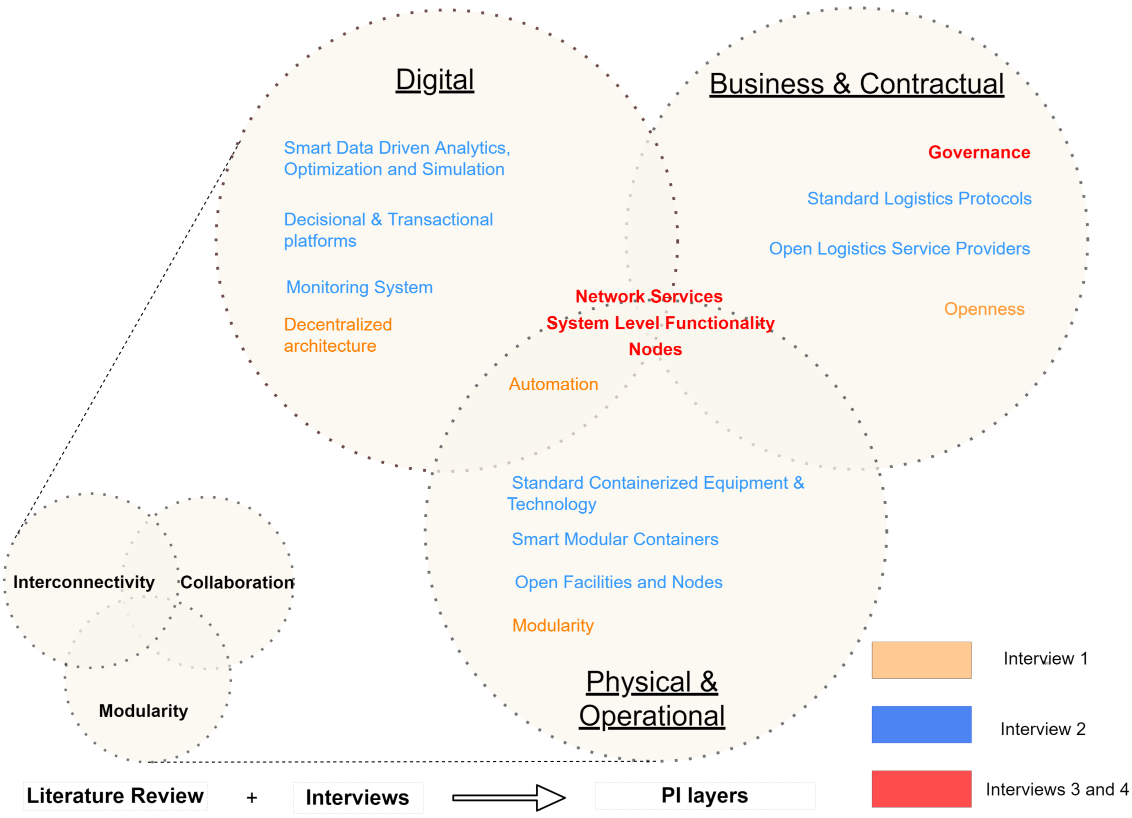


Figure 3.2: Resulting characterization of the Physical Internet from the Systematic Literature Review.

The wording of the different elements is of upmost importance to avoid misunderstanding by the panellists from the Delphi study in Chapter 4. Based on this, and for simplicity reasons, the three layers mentioned above are renamed into three distinct dimensions. These will be considered as the "PI characteristics" of the research, and are defined as follows:

- **Operational dimension.** This dimension refers to how transport is physically executed and operated by the different elements in the transport network, from hubs, warehouses, vehicles or handling equipment.
- **Digital dimension.** This dimension deals with the digital connectivity of the different players in the logistics network. A system is in place so that the actors can share information, communicate with each other and make decision for optimized transport networks.
- **Governance dimension.** Businesses need rules and protocols in place for exchange of data, and goods within the Physical Internet, from individuals and smaller businesses to the bigger companies. The "Governance Dimension" refers to this set of rules for a cooperative, safe an reliable PI environment, in line with the definition given from the SENSE workshops [see Appendix B].

A visualization can help understand the generalized PI characteristics derived in this thesis. Looking again into the lower levels of the freight transport system framework proposed by Tavasszy (2006), the PI freight transport system would somewhat look like Figure 3.3. Three overall dimensions are considered, which together enable a transition from independent, firm-based logistics networks to an open interconnected "network of networks", as envisioned by E. Ballot et al. (2014).

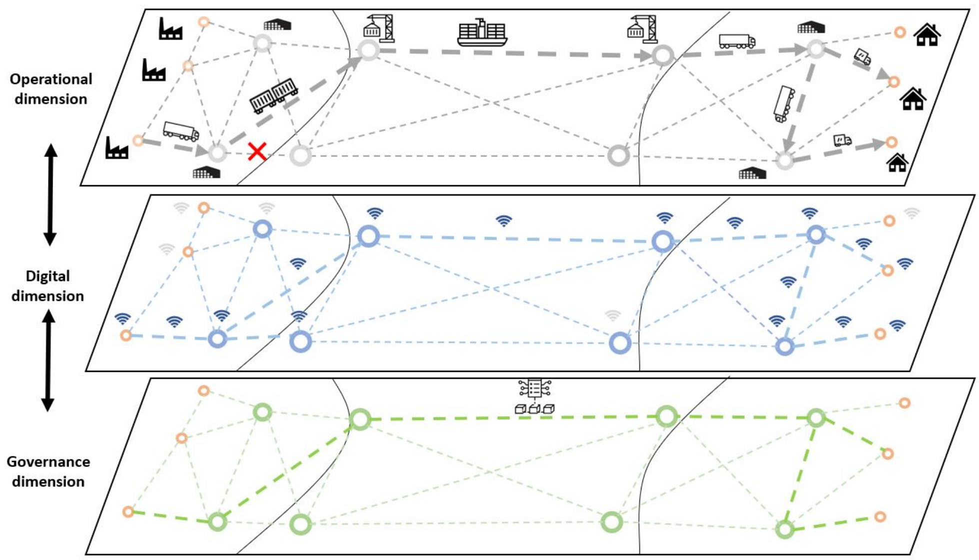


Figure 3.3: PI freight transport systems according to the three PI dimensions proposed by the author.

In the uppermost dimension, the transport network can be depicted. Physical elements such as hubs, vehicles, handling equipment or even the linking infrastructure are considered, as well as the physical operations such as the moving, shorting, or handling of the goods.

Nodes can be categorized hierarchically into different tiers depending on the range of physical connectivity they provide. From major global gateways such as seaports or airports to smaller intermediate cross-docking centers, following a meshed multi-layer network depicted by Montreuil (2019) or Aroca and Pruñonosa (2018). Goods can be encapsulated in a new generation of π-containers or make use of the existing unit loads, as suggested by the SENSE experts, and be moved around the different hierarchical nodes.

The lower dimensions make the realization of efficient operations possible depicted in the top layer. In the intermediate layer, a digital environment provides the necessary interconnectivity for transparency, robustness, real-time communication and information sharing among the actors, where the most efficient decisions regarding the routing or the way objects are moved throughout the network can be done in the top layer. This could be seen as an open digital "cloud", as suggested from the first interview, where information is shared across actors. The contractual terms and rules to be followed by the actors when sharing physical assets, information or goods is complete with the lowest layer, which sets the "rules of the game" within the PI.

The figure above provides an idealistic example on how the PI freight transport system could work in real life, with all nodes and vehicles being hyperconnnected. Individual players (consumers) located in the right hand side purchase a particular product from a factory or business located overseas (left hand side). After handling processes, goods are transported via π-certified logistics provided from this business to the most suitable intermediate π-hub, as suggested by the digital dimension and via an arrangement that binds all parties to perform their function. At this point, cross-docking processes such as unloading, reconfiguration, preparation, and loading can be carried out (B. Montreuil et al., 2013). Before departure, the next most suitable location is defined, as well as the mode and routing options based on factors such as slot availability, price, time and CO_2 emissions. In the example, due to a last-minute disruption of the physical link to the nearest maritime π-hub, the dynamic routing algorithm suggests in real time to move the goods via a different mode to the next best location, a deep-sea maritime π-hub. A similar cross-docking process is followed, where goods are then transported to the next best location, given real-time and expected capacity slots and hinterland connections. This π-node is automatically informed in real-time about the arrival of a vessel and therefore adjusts berthing capacity accordingly. Given the expected time of arrival, the vessel can adjust its velocity accordingly, so that waiting time is avoided upon arrival.

A similar processes is followed as before, where the goods are handled and moved onto the next most suitable intermediate node according to their available capacity. For some of the consumers, last-mile delivery processes are followed according to the most efficient route. For others, the digital cloud considers an extra intermediate leg to be necessary, since it can for instance help consolidate shipments of other consumers going in the same direction, while avoiding large miles for the drivers. Once the loading unit has been delivered to its final destination successfully, an automated invoicing and payment process starts according to the business or contractual dimension. Each actor has done its function and has been economically compensated or charged according to the contractual terms in which they were bounded.

It is important to note that, from the generalized conceptual idea of the Physical Internet herein presented, Figure 3.3 depicts a situation in which all players are hyperconnected, or part of the Physical Internet. In Section 3.2, from a particularization of the main PI characteristics to ports as transport nodes in freight transport systems, an evolutionary path of what will be referred to as "port connectivity" will be presented. In this framework, ports evolve in different levels and ideally reach the state of "hyperconnectivity" with the rest of the actors in the network.

3.2. PI Port framework

The previous section outlined a generalized characterization of the Physical Internet, with three distinct dimensions or layers that try to capture all the knowledge from both literature and the consulted experts. Based on this, the way freight transport networks would function in the PI was presented. Section 3.2.1 envisions how a hyperconnected maritime port, or "PI Port", would function under these new networks, using the research context from Section 1.3.2 as reference. Based on the previous, and several brainstorming sessions with MSc candidate Jeff Voster, Section 3.2.2 will propose a framework that shows the evolution of a single port towards a PI Port as a function of those PI dimensions. A reflection by the author upon the resulting framework is shown in Section 6.2.1.

3.2.1. Role of maritime ports in PI freight transport systems

To envision the role of maritime ports in PI-based freight transport systems, the visualization depicted in the previous section can form the basis to understand how these nodes would function. The uppermost physical dimension could be seen as a multi-plane meshed network, as depicted in Figure 3.4.

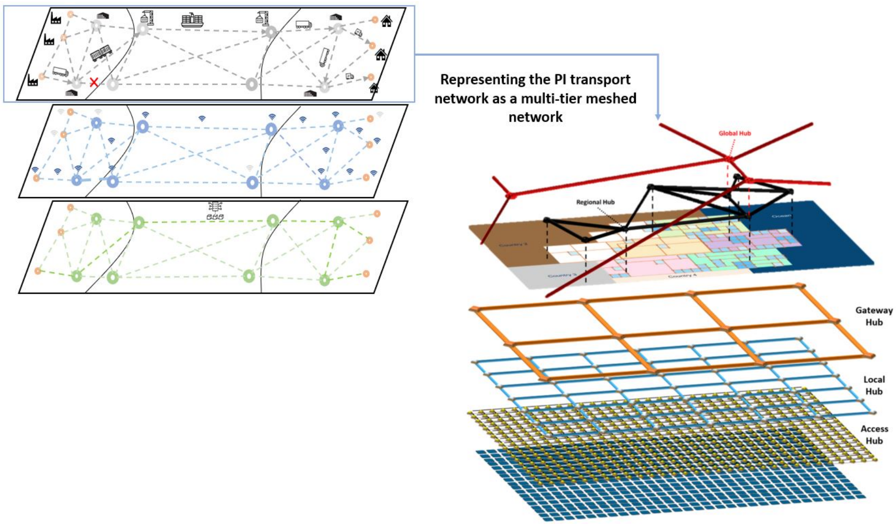


Figure 3.4: Linkage between the three PI dimensions proposed in this thesis and the interconnected multi-plane meshed networks proposed by Montreuil (2019).

Under this topology from Montreuil (2019), the lower tiers represent access or local nodes, where end consumers get their shipments delivered. Higher tiers represent bigger nodes such as open intermediate hubs which connect larger zones or areas at a broader scale. The highest tiers such as gateway or global hubs, where the Port of Rotterdam would be included, connect international regions horizontally with other global PI hubs. Adjacent planes are connected vertically by inter-hub links. Not only is the linkage possible from a physical dimension, but also from the other two dimensions already discussed in the previous section.

Getting back again to the initial definition of "maritime hub" considered in Section 1.3.2, it is argued here that, with the full deployment of all the PI dimensions, global PI ports would be:

1. Open nodal points of smart (modularized) container transit or transshipment, located to connect land and sea, assuring flawless door-to-door container movement through standardized equipment and digital and contractual interconnectivity with the rest of the actors in the chain.
2. A principal distribution center functioning as a temporary storage through open terminals which offer in real time available capacity.

3. A place for value-added services on the regional and/or international scale.

The first point refers to the main function of maritime ports in transport networks, yet upgraded to the new standards of the Physical Internet. These global hubs are composed of open terminals which are considered as open nodes themselves and are certified to operate π-services. Each of these sub-nodes would be physically composed of tailored and standardized handling and transshipment equipment, such as automated π-cranes or π-terminal trucks. These physical components would have autonomy to communicate with other components situated in the same hierarchical layer[3].

Accepting the premise that, under the PI, container average occupation rates will increase, the number of idling or unnecessary containers in the yard areas could be subject to decrease. This can translate to less occupancy of the yard area, which can eventually lead to oversized current terminals. This however can be offset by two factors: (1) the expected increase in international freight cargo already mentioned in Chapter 1; and (2) lower levels of predictability expected within the PI. As suggested by Sallez et al. (2015), very limited time windows to react would be the new norm in transport networks. Space buffer would be needed to accommodate for last-minute disruptions, and therefore the second function of maritime hubs would be to provide such temporary storage. Within the digital dimension, terminal nodes could offer, under a particular control architecture (i.e. hybrid), forward looking space capabilities for the rest of the network, as well as robust reactive protocols in case of a disruption.

Value-added services within the port domains are also expected to co-exist in the PI. Regarding those for the transport means (vessels, trucks, etc.) services would be highly tied to the new requirements of the vehicles. Cleaning or watering services can be among some of the services to be provided, depending on the level of human intervention of these modes within the PI. For completely autonomous vehicles, services would be limited to those required within the new regulations required for such modes.

From a logistics perspective, value-added activities could be reduced to a cross-docking process in the intermodal terminals, as proposed by B. Montreuil et al. (2013). Upon arrival of a vessel, boxes would be unloaded in the receiving zone and then sent to either a stacking area or a nearing reconfiguration area. The former would be destined for those boxes which are ready to be loaded onto the next mode. The reconfiguration area would act as a preliminary filter where boxes are detached and grouped to the best match according to the dynamic algorithms. Once these new composite containers are ready, they can be placed in the stacking area, and be ready for loading into the next mode of transport.

3.2.2. Evolution path of port connectivity

The previous section outlined how a port would generally function as a fully developed PI hub, in a fully developed PI network with other PI hubs. Nevertheless, many external factors are subject to affect how the different dimensions of the PI will evolve. For that reason, an evolution path of the PI dimensions and their influence in the development of maritime ports is proposed. As discussed in Section 1.3.2, literature is rich in the field of port evolution, and has been subject to constant debate and reformulation over the years. Yet, there is consensus on several aspects such as the ongoing vertical and horizontal integration of shipping lines. Because of the similarities in the research scope, the generation approach taken by the SENSE experts from Interview 3 and Interview 4 could be used at this point [see Appendix B]. However, there are several differences to take into account:

- There is now a particularization from the entire transport network, which was the focus of the SENSE workshops, to maritime ports.

[3] A Multi-Agent control architecture such as the one envisioned during the first interview could serve such purpose.

- The term "generation" could be seen as rigid and static, as was the case with the "port generation" approach used by the UNCTAD. Instead, the term ´levels´ can be more appropriate.

For these reasons, an adapted version of the generations approach taken by the SENSE experts will be used instead. Each dimension evolves individually, following different "ladders" in time (Lee & Lam, 2016). They then determine, at a particular point in time, how far the "system level functionality" has gone, referring to this as the way the different actors function in freight transport systems, from separated sub-networks at a firm level to globally connected firms. "Connectivity" in this sense is not considered only from a digital dimension, but also from a physical, operational and contractual. It is relevant to define here how a maritime port would evolve from its current state towards a PI Port. Up to 5 stages, in collaboration with Msc candidate Jeff Voster, of "port connectivity" are therefore proposed, from Current State to Level 4.

Current state

As already mentioned in Chapter 1, recent developments towards port regionalization were dominated by global consortia and maritime alliances which has increased horizontal and vertical integration in maritime transport chains (Heaver et al., 2001), with a concentration of the top players.

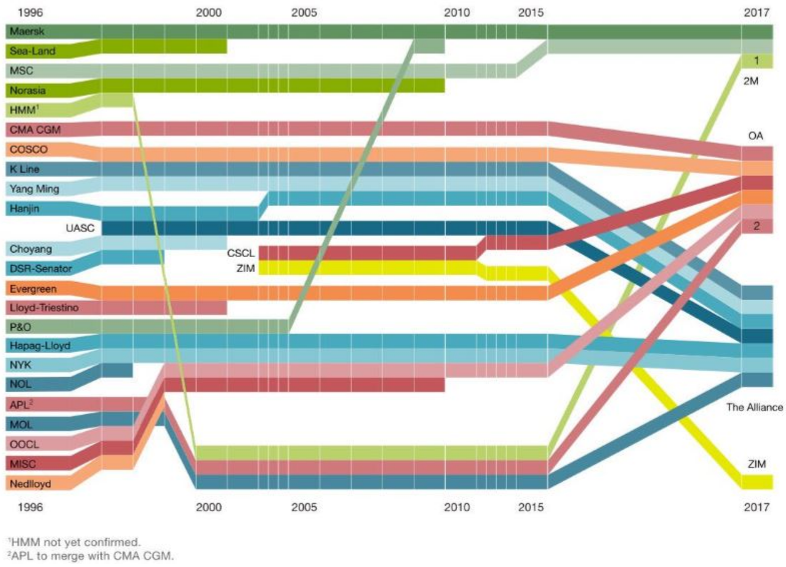


Figure 3.5: Global alliances of shipping line companies. Source: McKinsey & Company.

Following the SENSE approach, if one considers a port domain as a company and each terminal or actor as a particular department within the company, it would be reasonable to consider a current state of "silos within silos". Cooperation between terminals is nearly non-existent, as pointed out by Heaver et al. (2001) or Pfoser et al. (2016).

Yet these terminals are being subject to a vertical integration of the aforementioned alliances. This can be visible, for the case of the Port of Rotterdam, in the Maasvlakte 2 area. A handful of shipping lines have become hybrid operators. That is, firms where their main business, or that of the parent company, is still container shipping, but where a separate terminal operating division or company has been established. A clear example is the the operator APM Terminals, a firm belonging to the A.P, Moller-Maersk Group. APM Terminals acts as the node and the Maersk Line as the linking vehicles, both by sea and by land, given recent announcements[4]. Another example is the neighboring terminal operator ECT, which is already developing dedicated corridors in the European hinterland[5].

[4]The Maersk Group recently announced the merge of Maersk Line and its trucking subsidiary Damco, see link.

[5]See European Gateway Services.

Similarly, Rotterdam World Gateway is an automated terminal which belongs to the international consortium of DP World and the shipping lines APL, MOL, HMM and CMA CGM[6]. The current state could therefore be considered as in Figure 3.6, where ports are composed of dedicated terminals, some of which are part of major alliances which integrate supply chains vertically. For visualization purposes, the coloured nodes refer to the examples already mentioned before (red-APM Maersk; green-DP World; yellow-ECT).

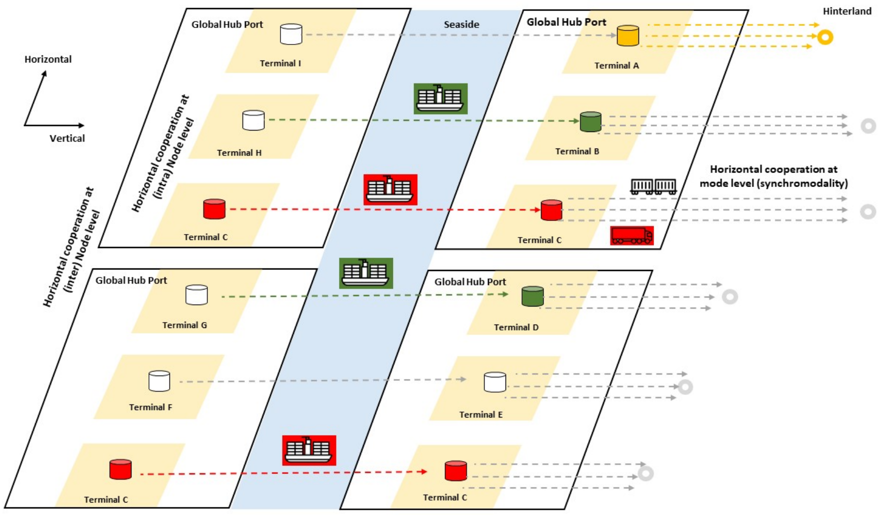


Figure 3.6: Global ports (nodes) broken down into terminals (sub-nodes) in current transport networks dominated by consortia and alliances.

Considering the **"digital"** dimension from Section 3.1.3, small niches are under development in the current state, with Blockchain, IoT or AI leading the path. Track and trace systems within the firms or alliances are starting to be tested and implemented, which improve transparency of the shipping, reduce costs and eliminate redundant paperwork [7]. Ports are also digitizing processes through the so-called Port Management Systems (PMS), which collect data from various parties inside the port to improve efficiency and transparency of operations while reducing redundant administrative paperwork. The Pronto platform is a good example inside the Port of Rotterdam[8]. At terminal level, Multi-Agent control architectures are also being tested to replace current manual operations.

One-to-one agreements are the norm in the **"governance"** dimension. Standards and definitions are still scattered and unbalanced, and for that reason the regulation of small PI-like niches are still needed. The "Rotterdam Rules", which were approved in December of 2008, are meant to replace the current Incoterm rules, and aim to modernize and standardize conventions on the carriage of goods by sea, and reduce liability risks for many parties involved in the international maritime transport chain[9]. The Rotterdam Rules therefore contribute to legal uniformity and certainty, and are meant to be more flexible than the reactive Incoterm rules, as suggested during Interview 3 with Prof. Tavasszy. Its entry into force is expected not to take long in the Netherlands, partly dependant on its ratification by neighbouring countries, such as those in the HLH range, and major trading partners such as China and the USA[10].

Furthermore, the EU law generally bans agreements between companies that restrict competition (antitrust). However, the maritime "Consortia Block Exemption Regulation" (CBER) allows, under

[6]See DP World.
[7]A recent example could be the blockchain project between Maersk and IBM. See link.
[8]See Pronto Port Call optimization platform.
[9]See Rotterdam Rules.
[10]See link about the ratification of the Rotterdam Rules.

certain conditions, shipping lines to enter into cooperation agreements to provide joint cargo transport services. Such antitrust exemption of Article 101 of the Treaty of the Functioning of the European Union (TFEU) expires in April of 2020. The decision to expire or extend it is currently under consultation[11].

Within the **" operational"** dimension, the automation of handling operations within the terminals are under way, with a faster trend at the yard itself than at the quay gantry cranes (Martín-Soberón et al., 2014). Moves within the terminals at the PoR are totally or partially automated, with APM at Maasvlakte 2 being a forerunner worldwide since it combines high levels of automation at the yard and at the the quay cranes. Current standard containers are still the loading units. Some terminal operators are starting to offer synchromodal services to combat potential inefficiencies in the hinterland, with ECT as an example.

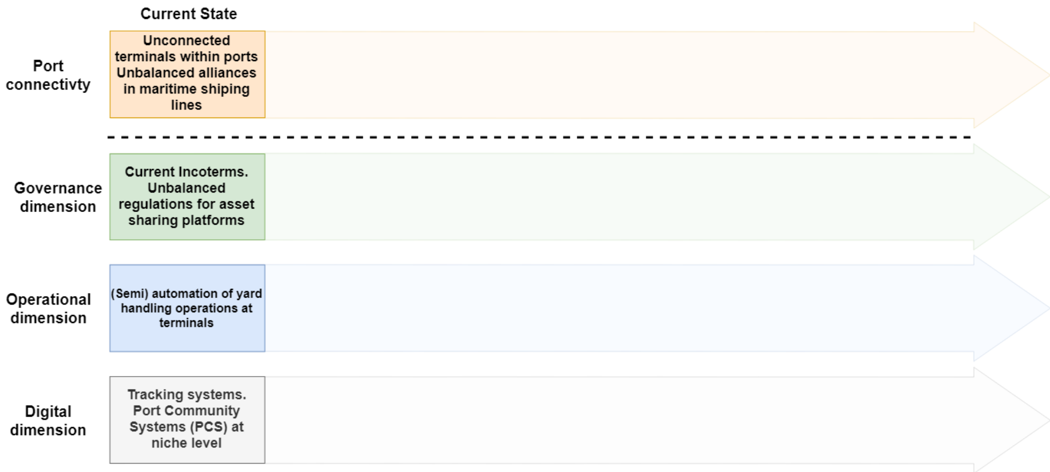


Figure 3.7: Current State in terms of port connectivity.

Level 1: Full vertical integration of alliances

Following the same line of reasoning as the SENSE workshops, "Physical Intranets" are achieved at firm level. Translating to the shipping lines domain, complete vertical integration would be expected within the alliances, such as the Maersk Group integrating sea ports, inland ports, and shipping lines. This could be seen as a form of cooperation within supply chains. To reach this first level, the proposed three PI dimensions need to evolve as well.

At the **"digital"** layer, a centralized control architecture could bring connectedness to all the players within the Port or Rotterdam, while digitally connecting as well with the hinterland for visibility of the entire supply chain[12]. A fully developed Port Community system such as PortBase[13] could allow for communication between the different parties. On a Business-to-Business (B2B) basis on the one hand, with respect to general quests (ETA/ATA/ETD), and on a Business-to-Government (B2G) basis for administrative purposes (Customs, IMOFAL). At the same time, booking platforms such as EGS keep scaling up and developing in other terminals.

In the **"governance"** layer, data ownership and control arrangements would need to be solved for trusted information sharing processes. The ratification of the Rotterdam Rules could set the path for further standardized agreements that protect data privacy while ensuring the benefits of digitized operations. Likewise, the extension of the antitrust exemption (CBER), or the entry into force of

[11] See press release by the European Comission, which dates to the 27th of September of 2018.
[12] See Cassandra project.
[13] The Digital Maturity Model follows a similar bottom-up pathway proposed in this section with respect to the digital dimension. See link.

a similar regulation that sets the path for flexible cooperation among the different players, while avoiding oligopolistic behaviour in the industry, can set out the path for increased connectivity[14].

Moreover, as suggested in the third interview, the Rotterdam rules could solve bottlenecks in synchromodality such as liability issues, which would be the new stage within the **"operational"** layer. Further automation of handling operations at the yard are reached, with the quay cranes still following the path towards automation.

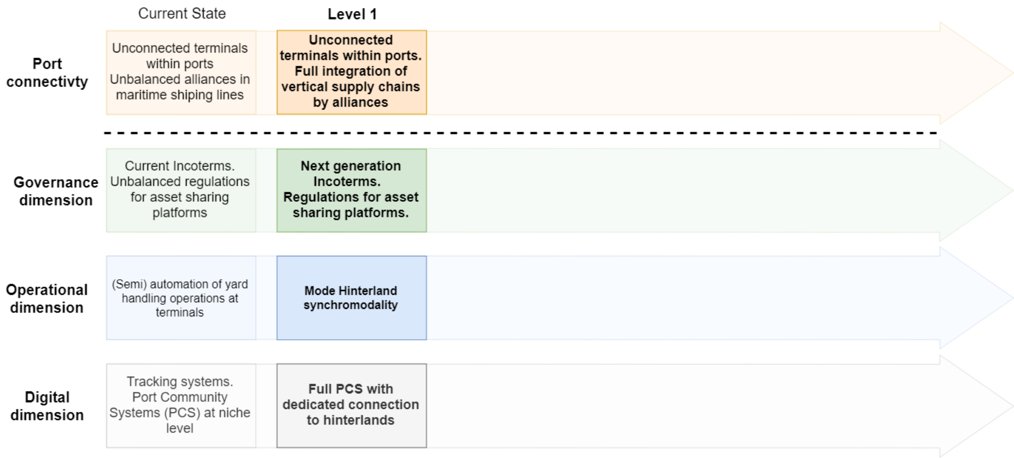


Figure 3.8: Level 1 of port connectivity.

Level 2: Open terminals within the port

In the previous level, dedicated terminals became part of individual vertically integrated supply chains, dominated by alliances that had reached hinterland nodes. In a next step, same cargo segment terminals are open and horizontally connected within the port. This level could be considered as the "Physical Intranet" of the entire port community. It includes inbound/outbound modes, the terminals, and any other governing body located within the terminal (Customs, Port Authority,...). In order to reach this "Physical Intranet", the three PI dimensions must also reach the following stages.

At the **"digital"** layer, a multi-layer decentralized control architecture within the port allows for direct communication and information sharing between the different parties, so that they can make the best decisions in real time. At this point, PortBase could fully connect inside the port as well as those located in the hinterlands.

Considering the **"governance"** layer, standards and contractual rules, either in compliance with the exemptions of Article 101.3 of the TFEU[15], or with a modification that completely exempts port activities from antitrust regulation, are implemented for asset sharing at the entire port level, with connectivity of both terminals and modes. Lastly, in the **"operational"** dimension, with open terminals, cross-docking and reshuffling operations of load units are now possible not only within but also between terminals. This processes are done automatically with the handling equipment and following the guidelines of the decisions made by the control structure.

[14]It must be noted that the author assumes at this point that the exemption of the CBER, or the entry into force of a similar regulation that enables flexible cooperation, will take place.

[15]See paragraph 3 of Article 101of the TFEU: *the provision of paragraph 1 may by declared inapplicable in the case of [...] which contributes to improving the production or distribution of goods or to promote technical or economic progress, while allowing consumers a fair share of the resulting benefit.*

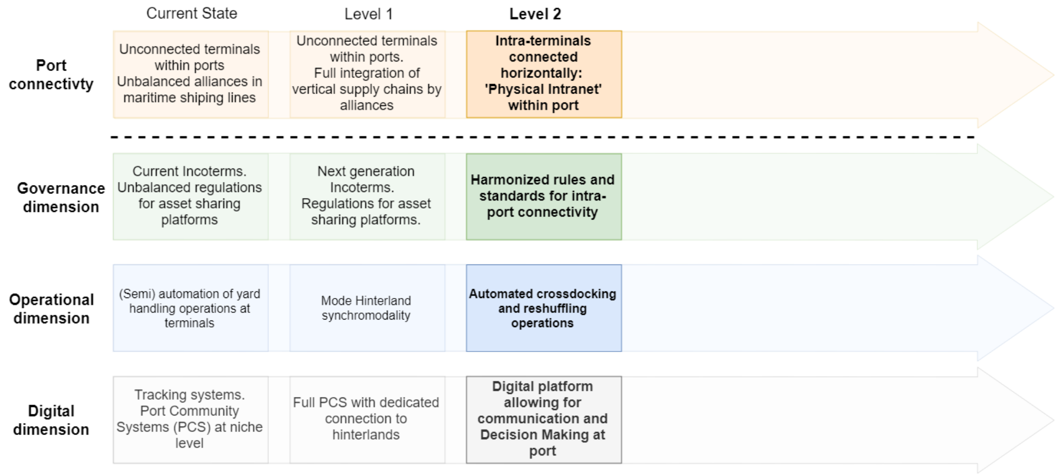


Figure 3.9: Level 2 of port connectivity.

Level 3: Open ports at regional level

At this level, connectivity of terminals go beyond the boundaries of the port itself, reaching other competing ports in the same region. Ports as global hubs become open to other hubs competing for similar hinterlands or supply chains, such as the HLH range. An example could be the connectedness between the PoR and the Port of Hamburg.

What allows such openness of the ports at an inter-network levels is first the next level of the **"digital"** dimension. Decentralized structures at hub levels connect horizontally with other decentralized control structures from other hubs, thus creating a multi-layer distributed inter-network standardized platform at a region level, such as the HLH range [see Figure 3.10 as an example].

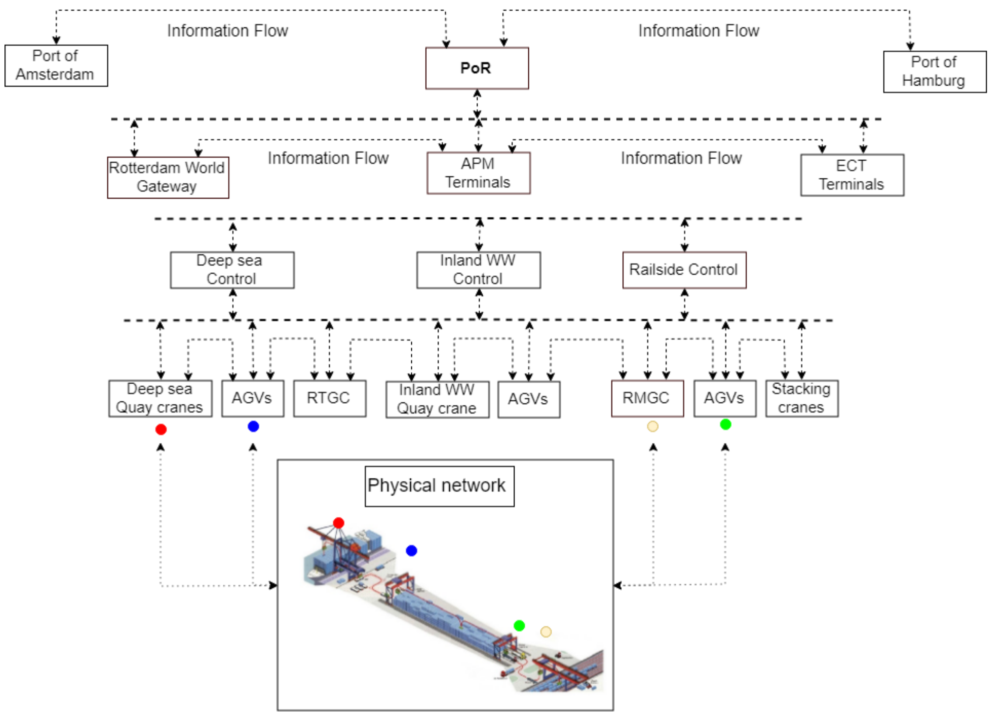


Figure 3.10: Example of a multi-layer distributed control architecture.

The main reason to not have a single-layer structure, where an AGV would be at the same level than the Port Authority, has to do with potential issues such as the following (Negenborn et al., 2010):

- Undesirable properties with respect to robustness, reliability, scalability, and responsiveness.
- Technical issues related to communication delays and computational requirements.
- Commercial, legal, and political issues related to unavailability of information and restricted control access.

Considering the **"governance"** level, a scaled up set of competition and standard rules that apply at a regional (European) level, which define liabilities, laws applicable at a particular country or the profit split among all the actors involved, need to be in place. All these in compliance with Article 101 of the TFEU or with any new legal framework that eases cooperation among the different parties.

At the **"operational"** level, nodes have the capacity to service and respond to disruptions across the networks such as outages, congestion or capacity constraints. Since data has become open and transparent, individual agents can automatically act according to the available information, as suggested in Figure 3.10 above.

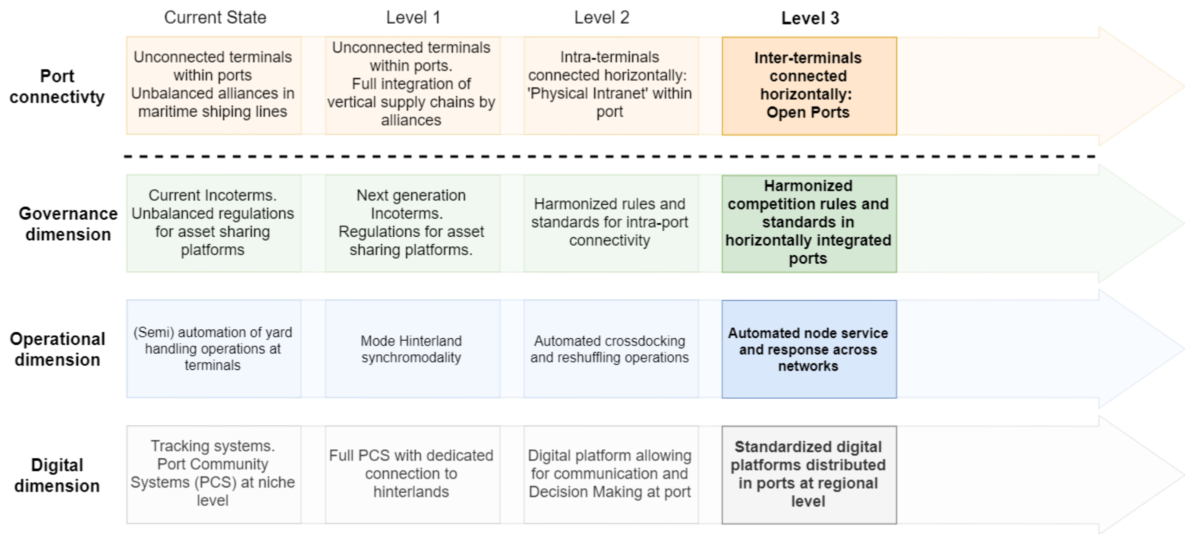


Figure 3.11: Level 3 of port connectivity.

Level 4: Global hyperconnected hub

The last level can be considered the full roll-out of the Physical Internet globally, and results from a generalization of the previous level to global networks, where border protocols connect regional areas, as suggested by Aroca and Pruñonosa (2018). This means that not just joint actors in Europe, but also in other areas such as Asia or the US, make that step beyond their region domains. In this situation, the PoR would be connected, through a global distributed control structure, to the Port of Singapore, another global hub in the PI network. Operations at the port are done autonomously, exploiting the benefits of open networks. For national security reasons, governing bodies ensure that rules respect the sovereignty and integrity of the different nodes, avoiding worldwide monopolies within the PI and ensuring "seamless, secure and confidential data exchange" (Treiblmaier et al., 2016). Figure 5.1 summarizes the PI Port development framework derived from the previous paragraphs. As can be seen, the three building blocks, which came from a particularization of the general PI dimensions, affect the evolution of the the port into a "PI Port" in time. The connectivity of the port as a hub jumps upwards to the following stage as the three PI dimensions together do so to the next level.

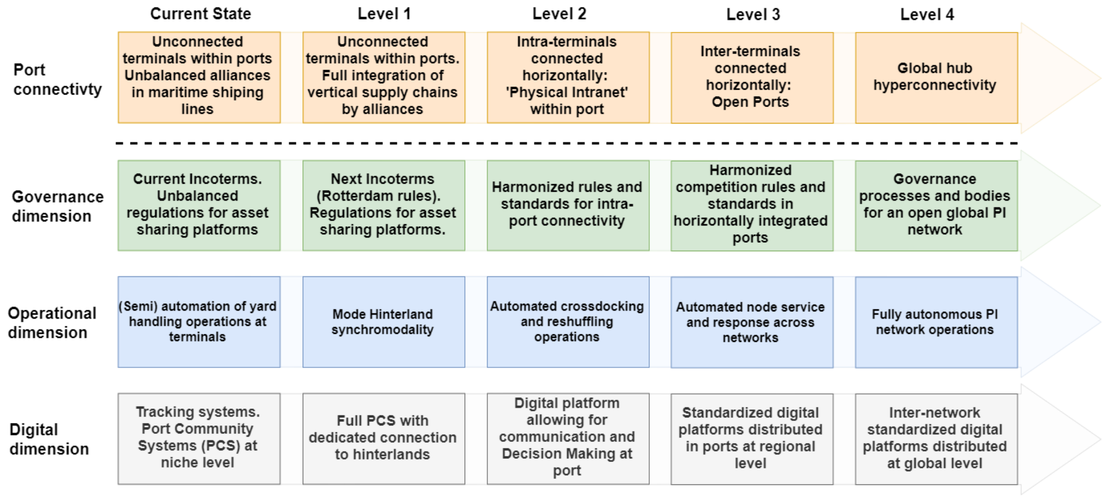


Figure 3.12: PI Port framework. Evolution path of three dimensions which influence the development of port connectivity towards a hyperconnected hub, or "PI Port".

The proposed bottom-up approach tries to capture an evolutionary path of maritime ports in the context of the Physical Internet. First the Physical Internet would be achieved locally (up to Level 2 with open terminals within the port or "Physical Intranets"), then regionally (Level 3 with open ports within the same region, such as Europe) and finally at a global context (Level 4 with open ports hyperconnected globally). The framework starts zooming into a maritime port, and therefore scaling up from the local to the regional context means that neighboring ports make the transition as well. Likewise, connecting with other ports globally translates to other regions scaling up to the global hyperconnected system. The last stage could be seen as the formal definition of the Physical Internet from B. Montreuil, Meller, and Ballot (2012), and by showing an evolutionary path, the proposed framework tries to break the misconception, already identified by Treiblmaier et al. (2016), that there is a "binary state in which the PI either exists or not". Rather, the Physical Internet can first be gradually achieved in local or regional areas, and then scale up to the global level. Besides the similarities with the "PI generations" approach from the SENSE experts, the proposed framework also goes in hand with the bottom-up approach of the Digital Maturity Model proposed by the Port Authority of Rotterdam, which focus the evolutionary process on the digitization of port communities, broken down into four steps [see Appendix C].

The evolution of the three PI dimensions, and therefore the port, is dependant however on an external environment which will affect how far they will develop within a period of time. The entire framework will be considered as the "system", which will be affected by the contextual factors in the next chapter, following the guidelines from Enserink et al. (2010). Since relevant driving forces will be selected based on the impact and uncertainty on the "system", the later will be strictly defined as *"the evolution of three PI dimensions which influence the development of the port towards a PI Port"*. In Chapter 4, experts will be consulted through a Delphi survey about the level of development of each of the three PI dimensions at a particular point in time, for different contextual scenarios. Based on the output from the Delphi, the author will derive the evolution path of port connectivity.

Furthermore, this is, to the best of the author's knowledge, the first attempt to visualize the evolution of a port into a PI port. The framework proposes a fixed ordering of stages, and by joining them, one can visualize a linear or non-linear evolution path, both for the PI dimensions, assumed to be independent, and the port itself, from the local to the global level. With the hope to enrich the debate around the Physical Internet and the evolution of maritime ports, experts will be given the chance to provide their feedback on the proposed framework.

4

Scenarios

This chapter first elaborates on the different contextual scenarios, and then on the Delphi study, which feeds on the previous to determine the "PI scenarios", which outline the evolution path of port connectivity as a function of the development of the PI characteristcs. Firstly, following the guidelines from Enserink et al. (2010), contextual factors are determined and clustered into driving forces in Section 4.1. Those with the highest impact and uncertainty on the "system", which was the outcome of Chapter 3, are further used to generate of contextual scenarios in Sections 4.2 and 4.3. To determine the evolution of the Physical Internet within maritime ports, for each contextual scenario, a Delphi survey is used, and its structure and results are presented in Section 4.4. Based on the outcome of the Delphi, the evolution path of the PI Port is outlined in Section 4.5 for each PI scenario. Lastly, in Section 4.6, general recommendations for the Port of Rotterdam are outlined.

4.1. Driving forces

A total of 39 contextual factors in the field of supply chain and logistics were identified from literature, reports, the conducted interviews, and brainstorming sessions between the author of this thesis and MSc candidate Jeff Voster. Through a brainstorming session and logic reasoning, the contextual factors were clustered into different proposed driving forces that would try to avoid overlapping between them as much as possible. A first filtering was done on those contextual factors that could not clearly be allocated to a particular driving force, or were overlapping with other contextual factors, and therefore they were removed [see Appendix D]. The resulting 32 contextual factors and 7 driving forces are shown in Table 4.1. Sections 4.1.1 to 4.1.7 outline each of the driving forces, and study their "impact" and "uncertainty", so that the most relevant are further considered, through the following logic:

- **Impact:** To assess the "impact on the system", the author reasons whether *"this driving force has a clear impact on the evolution of the three PI dimensions from the PI Port framework* (large impact) *or not"* (small impact). In other words, a clear and direct causality between the driving force and the 3 PI dimensions from Section 3.2.2 is detected or not, and whether it is large or not.
- **Uncertainty:** To assess the "uncertainty", the author reasons whether *"there is a clear development path or direction of this driving force"* (small uncertainty) *or not"* (large uncertainty).

The logic reasoning followed during the clustering did not avoid strong inter-dependencies between some of the identified driving forces. For that reason, besides assessing the impact-uncertainty relevance individually, the purpose was to arrive at a final set of relevant driving forces that would not fully influence each other. In other words, a selected relevant driving force should be allowed to freely move, to a large extend, in one direction or another, regardless of the development of another selected relevant driving forces.

Table 4.1: Final contextual factors clustered into the proposed driving forces.

Flow patterns*	**Technological innovations**	**Global institutional integration**
Melting of Artic Pole	Internet of Things	Political union in Europe
Belt and Road Initiative	Big Data	Trade agreements
Increase vessel size	Artificial intelligence	Import tariffs and quotas
Nearshoring	Blockchain	Different tax environments
Economic growth	Drones	National subsidies
Circular economy	Hyperloop	
Mass individualization	3D printing	
Demographic changes	**Climate change**	**Business models**
Population growth	Pollution	Cooperative models
Migration flows	Rise of temperatures	Global monopolistic operators
Urbanization	Environmental policies	Innovative business
		Individualistic models
Regulatory frameworks		
Cybersecurity		
Antitrust policies		
Labor protection		

*It would seem reasonable to consider that all driving forces, an corresponding contextual factors, influence "Flow patterns". For clarification purposes, the author considered in this case the remaining contextual factors that could only be clustered into this driving force.

4.1.1. Global institutional integration

Institutions can be defined as "the humanly devised constraints that structure political, economic, and social interactions" (Williamson, 1998). Considering the second level of the framework by the aforementioned author [see Appendix], this category refer to the formal institutions that set the "rules of the game". That is, national constitutions, transnational integration projects such as the European Union, or any other supranational agreements. In the context of the thesis, this driving force refers to the global integration from an economical and political perspective. Several factors affect it, from the measures to protect domestic industry against foreign competition (protectionism) to the trade agreements between economic powers (nextnet.a, 2017).

Looking into the European level, the economic crisis of 2008 sparked nationalistic discourses and debates in the European Union (Wodak & Boukala, 2015). The recent Brexit referendum has questioned the integrative approach of the EU project, which can bring exposure to many countries. Yet, the effective impact on regions will depend on the negotiation agreement that will be reached for each single sector and the weight that each sector has in the productive structure of that specific sector (EC, 2018). Transnational free flow of goods and services can be threatened with protectionist policies, such as import tariffs, national subsidies or different tax environments (nextnet.a, 2017), or even military intervention[1]. At the global level, a similar protectionist trend can be seen with the recent political disputes between the US and China[2].

As can be seen, the institutional environment, whether it moves in one direction or another, can strongly affect not just global supply chains spatially, but also other political, social, environmental, legal, technological or economic matters. For that reason, this driving force can be considered to have a **large impact** on the evolution PI dimensions.

Regarding the "uncertainty" of its development, that is, the direction that the level of integration takes, it is hard to predict how this driving force will move in the next 20 years. On the one end, globalization could keep its pace steadily, with fewer trade barriers and sparking strong economic

[1] A recent example could be Russian-Ukranian conflict, which impacts trade relations, see Reuters.
[2] For a quick review of the US-China trade way, see link.

growth in developing countries. On the other end, a much more protectionist world could be envisioned, with power blocks protecting their markets against external industries. Therefore, the author considers this driving force to have a **large uncertainty**.

4.1.2. Flow patterns

As it was already mentioned in Chapter 1, understanding future global maritime freight systems is of upmost importance for the long term strategy and decision making of port authorities. Uncertainties in terms of volume traded and spatial shifts could affect how maritime ports evolve (Tavasszy et al., 2011).

There are many global factors which can disrupt global patterns, ranging from the "One Belt One Road" initiative promoted by China [3], to the melting of the ice in the Artic Pole[4]. Another concept that might influence global supply chains is "nearshoring", where as developing economies grow, work is reallocated to other low-wage countries. The increase in vessel size could be another trend affecting trade patterns and also ports T. Notteboom and Rodrigue (2009). Only those harbors which have invested, among others, in enough dredging and berthing infrastructure, will be able to accommodate and serve such ships. This would match with the "bigger and slower" trend that has driven the development of container vessels in the past 50 years. Trade agreements can also affect global supply chains, yet this was considered as part of the previous driving force ("Global institutional integration"), given that its impact go beyond spatial patterns.

From a societal perspective, consumer orientation have also an impact in flow patterns. From standard products with long lead times, these have evolved towards product customization with extremely short lead times (L. Tavasszy, 2018). Rising incomes, fueled among others by technological developments, have allowed individuals to demand more tailored products. Yet the orientation of consumers in the future might be influenced by rising concerns in terms of sustainability from a societal and environmental perspective. In this sense, the circular economy could continue gaining ground, fueled by further technological developments (nextnet.b, 2017).

As can be seen, global flow patterns can highly affect maritime ports. Yet, when assessing the impact on the 3 PI dimensions, such evidence is not so clear. For instance, the development of new control architectures, digital platforms or monitoring systems can develop faster or slower, yet independently from changes in flow patterns. Therefore, it is presumed that this driving force have a **small impact** on the "system".

Regarding the "uncertainty on the system", it would seem reasonable to assume that it is not clear how trade patterns will develop in the future. A **large uncertainty** is assigned to this driving force.

4.1.3. Climate Change

The world has been getting warmer during the past hundred years (Hansen et al., 2010). Whether the cause is human activity or natural variability, thermometer readings have risen all around the world[5]. Some studies suggest a high correlation between anthropogenic GHG emissions and temperature rise, concluding that human-induced pollution is "extremely likely to have been the dominant cause of the observed warming since the mid-20th century" (ipcc, 2014), and as a result, extreme weather conditions have become more frequent all around the world.

Climate change has been seen by some as the "mother of all externalities" (Tol, 2009), and its consequences can be very diverse. It can potentially impact agriculture, health and many aspects of

[3] Such project could result in a shift of economic centres and trade flows (PoR.c, 2018).

[4] The melting of ice could open up new maritime shipping routes between the Pacific Ocean and the Atlantic Ocean (Smith & Stephenson, 2013), yet the economic viability is still uncertain (Liu & Kronbak, 2010).

[5] The Earth Observatory from NASA provides a dynamic chart with the evolution of temperature anomalies from 1885 until 2014.

nature, which in turn can impact entire societies, with low-income countries as the most vulnerable of all (Tol, 2009). The economic consequences of the depletion of natural resources (nextnet.a, 2017) as a result of intense energy uses, and thus anthropogenic human emissions, have also been under debate in the past years[6]. Environmental policies are trying to tackle this issue. As an example, there is currently a target to reduce the greenhouse gas intensity of fuels by 40% from 2005 by 2050 for maritime transport (nextnet.a, 2017). It must be noted that the PI manifesto originated as a desire to revert the current transport and logistics practices which are considered by some academics as unsustainable, especially from an environmental perspective (B. Montreuil, 2011). In other words, the PI as a vision aims to ultimately impact climate change.

Since this driving force consider only the effects of climate change, as well as the policies to tackle them, it would seem reasonable to consider the "impact" of this proposed driving force on the PI dimensions is significantly large. Therefore, a **large impact** on the the evolution of the PI dimensions is given to this proposed driving force.

Nevertheless, in terms of "uncertainty" of this driving force, literature suggests that its development is expected to continue with current trends in the next years (ipcc, 2014), suggesting that there is **small uncertainty**.

4.1.4. Technological Innovations

This driving force encompasses technological innovations which could impact transport in general. On the one hand, Information and Communication Technology (ICT) such as Internet of Things, Big Data, Artificial Intelligence or Blockchain could be identified. These play an increasing role in the planning and management of supply chains, which could eventually change the way information is exchanged in transport networks (L. Tavasszy, 2018). Innovations such as blockchain could ease paperwork processing in ocean freight (nextnet.a, 2017) and support smart contracts[7].

Regarding transport innovations, faster modes such as the Hyperloop might eventually develop to satisfy increasing customer requirements in terms of time (Werner et al., 2016). In a similar fashion, new delivery capacities such as drones have been making real-world headlines recently, and could potentially replace last-mile delivery vehicles such as vans (WEF, 2016). Moreover, 3D printing could potentially revolutionize manufacturing and therefore the spatial distribution of freight transport systems, where production could be near the consumer (nextnet.a, 2017), or even at home[8].

It is important to note that each of the contextual factors have a varying "impact" when considered individually. It is difficult to predict the exact technologies that will be developed in the next 20 years. Yet it would seem reasonable to consider that those who develop will have a **large impact** on the evolution of the three PI Dimensions. As with previous technological breakthroughs, prices start off high around the introduction of new technologies, which initially discourage firms to acquire them (L. Tavasszy, 2018). As demand increases, and with flexible regulatory frameworks that allow for a fast adoption, prices drop until they break even.

Albeit accepting such initial economic barriers, what can be assumed is that the development of new technological innovations, be that in ICT or in transport in general, will not stagnate. In fact, the rising speed of innovation, fueled by easier access to information and accumulation of knowledge, has become an important pattern. For that reason, it is assumed in this thesis that this driving force have a **small uncertainty**. The adoption of these, however, will be subject by acceptance of society and especially regulatory frameworks that allow for their implementation. This is discussed in the following driving force.

[6]An interesting paper by Neumayer (2000) summarizes the point of discussion between resource scarcity or abundance and how it limits economic growth.

[7]"smart contracts" are electronic contracts based on automated actions, i.e. for automated execution of payments in case on an on-time delivery (nextnet.a, 2017).

[8]The "fabshoping" or home manufacturing is a potential application of 3D printing (DHL, 2012).

4.1.5. Regulatory frameworks

The regulatory driving force can provide support for the development of other driving forces. Looking again into the framework proposed by Williamson (1998), the "play of the game" can be identified in the third level. In here, the legal system is defined, and can change at a faster pace (from 1 to 10 years) than institutional environment located in the second level, which has a lower frequency of change over time (from 10 to 100 years).

Regulatory frameworks can have an impact beyond the governance structures. For instance, cybersecurity legislation that protect the rights of individuals and companies to ensure that their confidential information remains private might be crucial. In this sense, legislation lagging behind dynamic market developments can hinder a smooth digital transformation (nextnet.b, 2017). Data exchange needs to be regulated by cyber-secure peer-to-peer data networks, therefore avoiding data theft and the loss of data sovereignty.

Lastly, technological developments have brought wage cost reduction in many container terminals around the world. In northern Europe, many terminals have allocated financial resources on training programs so that workers can become multi-skilled (Turnbull & Wass, 2007). Because of this, the emerging terminal worker is becoming increasingly educated and trained. Yet, in other countries, such as in Spain[9], labor protection can create big bottlenecks to port development and hinder the adoption of new practices and technologies.

As can be inferred, regulatory frameworks have a **large impact** on many aspects and levels of abstraction, including the evolution of the three dimensions of the PI. The way it develops in the future will highly affect freight transport systems in general. It is interesting to see in the context of the PI whether regulatory frameworks will ease the deployment of technological innovations, also highly impactful. Labor protection can indeed be a bottleneck for the technological transition of many industries in particular countries. However, these two could be coupled, in the sense that regulatory frameworks could be hindering a technological transition partly due to a labor protection.

For any of the previous, it is difficult to predict the direction future regulatory frameworks will take, and whether they will develop faster or not. For this reason, a **large uncertainty** is assigned to this driving force.

4.1.6. Business models

A business model can be defined as a "new unit of analysis, offering a systemic perspective on how to do business, encompassing boundary-spanning activities, and focusing on value creation as well as on value capture" (Zott et al., 2011).

Business models can change according to the new market environments, from the (still dominant) individualistic, firm-based models to new forms of cooperation and collaboration[10] (Zott et al., 2011). They would go beyond the examples seen in the maritime sectors, where strategic alliances between the bigger market players paved the way for a state where global operators dominate freight transport networks.

As mentioned by some experts during the interviews, new innovative business models, which allow for flexible cooperation between the different players, could become more common. In words of B. Montreuil, Meller, and Ballot (2012), these refer to "innovative revenue and risk-sharing models for the various stakeholders". Examples of innovative business models could be "crowdsourcing" platforms, an asset-free concept in which all firms reveal transport prices, routes or service level [see (WEF, 2016) and (nextnet.a, 2017)]. As can be imagined, collaborative models builds upon trust

[9]The protection of the Spanish stevedores infringes Article 49 of the TFEU. See press release by the European Commission, which dates to the 28th of April of 2016.

[10]Albeit emphasizing the distinction between both terms in Chapter 3, collaboration and cooperation are used indistinctly in the context of this driving force.

of the different stakeholders to exchange and protect sensitive data for mutual benefit (Rougès & Montreuil, 2014). Competing service providers are not used to work together, and often are not even allowed to, given antitrust policies and regulations (L. Tavasszy, 2018).

This driving force could be considered as highly relevant, with a **large impact** on the evolution of the three PI dimensions. Nevertheless, as suggested by Pr. Tavasszy in his interview, the businesses will always seek to benefit from practices with the given rules and play of the game. In other words, if cooperative models allow companies to benefit, they will shift towards these practices. Yet, the extent to which those models will be implemented or not will be highly dependant on regulatory frameworks, the previously mentioned driving force. These allow for a faster transition and implementation of new technologies from which those cooperative models can be adopted.

This is also contemplated in the framework by (Williamson, 1998), where "business models" could be allocated in the fourth level, where not only prices and quantities, but also incentives are considered. They are situated below the third level, where "regulatory frameworks" was considered. In this sense, the causality relationship expressed by Pr. Tavasszy ("regulatory frameworks" affect "business models") is also represented in the aforementioned framework. As expected, "Global institutional integration" affects the rest of the driving forces, yet because of its frequency of change [see Figure 4.1], "regulatory frameworks", and thus "business models", can adapt faster to any changes in any direction that the former takes.

For these reasons, a **small uncertainty** is assigned to this driving force, considering that the direction "business models" take will be linked to the direction of "regulatory frameworks". Lastly, As will be explained in Section 4.4, there is also a practical reason to merge the former in the later, which has to do with the length of the Delphi survey.

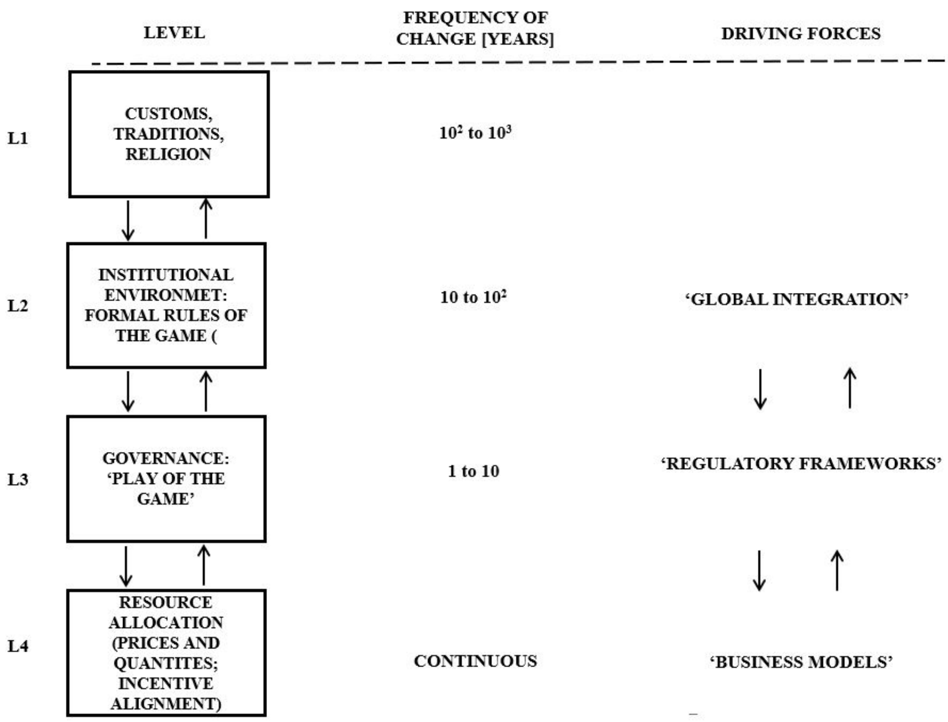


Figure 4.1: Relationship between the framework by Williamson (1998) and the three driving forces.

4.1.7. Demographic changes

Population, which is highly linked with anthropogenic emissions (ipcc, 2014), has been steadily growing throughout the last centuries, and this trend is expected to continue, however at a slower pace than before (UN, 2017).

Another contextual factor that emerged under the driving factor demographic change is "migration flows". These are mainly fueled by conflicts in different regions or lack of employment opportunities in less developed regions (nextnet.a, 2017). Such inter-regional patterns can also be seen when zooming into cities, where more than half of the world population live in nowadays. Their attraction has been fueled by job opportunities and the range of services it offers, at the expense of the countryside. This migration flow has generated an urbanization process (TLI, 2012), which has had consequences for cities.

Albeit increasingly becoming a challenge in the 21st century from a societal and environmental perspective, the "impact" of the demographic changes on the three PI dimensions is not fully clear. A direct causality could not be argued that easily, and for that reason a **small impact** is assumed. What is more clear however is the direction it will take. Demographic projections by different studies such as UN (2017) suggest how population will evolve in the upcoming years. For that reason, a **small uncertainty** to the development that this driving force is considered.

4.2. Selection of the relevant driving forces

The previous section described the different driving forces and the relevance each one had on the "system", which was the outcome of Chapter 3. Table 4.2 summarizes the level of "impact" and "uncertainty" of each of them:

Table 4.2: Summary of "impact" and "uncertainty" of each of the identified driving forces. Selected forces in bold.

Driving Force	Impact	Uncertainty
Global institutional integration	**Large**	**Large**
Flow patterns	Small	Large
Climate change	Small	Small
Technological innovations	Large	Small
Regulatory frameworks	**Large**	**Large**
Business models	Large	Small
Demographic changes	Small	Small

As already mentioned, the author acknowledged that the driving forces were not fully orthogonal, meaning that inter-dependencies were spotted. The remaining two driving forces were considered to be "global institutional integration" and "regulatory frameworks". The former indeed influences the later, yet through the lenses of the framework by Williamson (1998), the author argues that the frequency of change suggest that the lower level ("regulatory framework") can easily adapt to any direction the higher level takes ("global institutional integration").

The author considers the chosen combination to be constrained enough while giving sufficient spread in the scenario logic and room for imagination to the experts without overlapping. To confirm this hypothesis, the Delphi survey will give room to experts for feedback on this matter, and ask them whether the scenario logic is detailed enough.

4.3. Scenario logic

Once the most relevant driving factors are selected, the scenario skeleton that spans the scenario logic can be outlined, as proposed by Enserink et al. (2010). Such space can be represented in a two dimensional axis, as in Figure 4.2.

As can be seen, for each driving force, their two opposite directions [expressed as (+) and (-)] are outlined. Each quadrant of the figure, which represents a contextual scenario, equals a particular direction combination of the two driving forces, as shown in Table 4.3. The four contextual scenarios, which are used as input for the Delphi survey, are fully described in Appendix E.

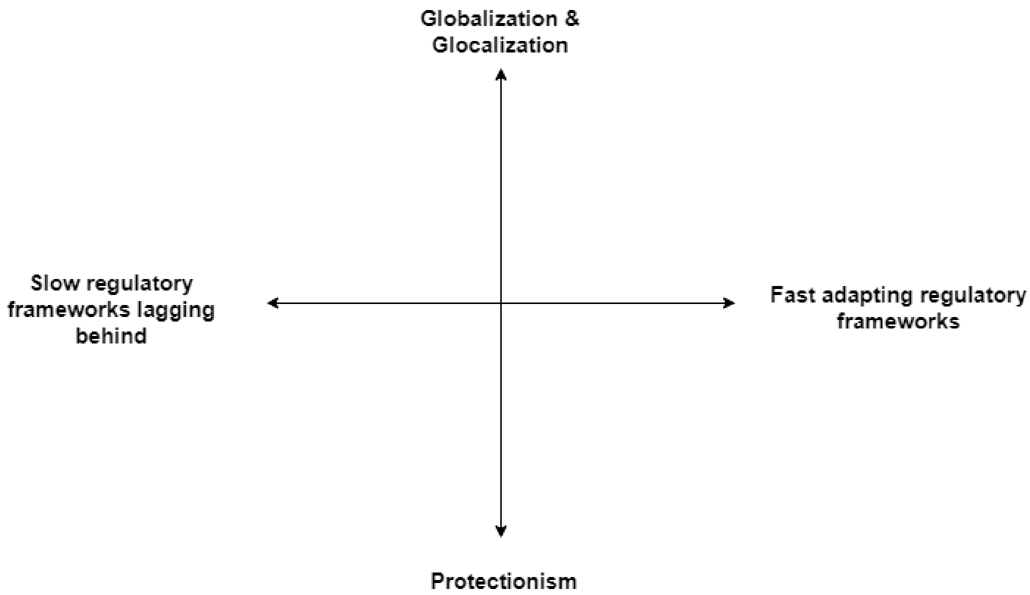


Figure 4.2: Scenario logic based on the two selected driving forces.

Table 4.3: Resulting scenarios as a combination of the two driving forces.

Scenario	Global institutional integration	Regulatory frameworks
1	(+) Globalization	(+) Fast adapting regulatory framework
2	(+) Globalization	(-) Slow regulatory framework
3	(-) Protectionism	(+) Fast adapting regulatory frameworks
4	(-) Protectionism	(-) Slow regulatory framework

As will be explained in Section 4.4, the purpose is to ask experts how far, in a categorical five-point scale, under each of the contextual scenarios, the three PI dimensions will reach until the year of 2040, which is the target goal considered in the ALICE project. Since evolution might not be linear and could follow a different time path, the year 2030 is also considered. The author acknowledges that adding an extra point can bias the results due to anchoring effects[11]. With the years 2020 (considered as the current year), 2030 and 2040 separated almost by the same period in time, the vision of an expert regarding one particular year might bias the others. Because of this, as will be explained in Section 4.4.4, the Delphi was also used as an opportunity to check with the experts whether they considered as adequate to ask for both points in time (2030 and 2040).

[11] The book *Thinking fast and slow* by Kahneman (2011) provides a deep foundation about how people can be influenced in surveys due to anchoring effects.

4.4. Delphi survey

This Section deals with the Delphi study, which uses the resulting contextual scenarios of previous Section 4.3 and the PI Port framework from Chapter 3 as input for the experts. Sections 4.4.1 to 4.4.3 outline both the expert selection criteria, the chosen tool and the structure of the questionnaire for Round 1 and Round 2, respectively. In Section 4.4.4 the results from the survey are presented, which includes the statistical results, including the degree of consensus, and the results from the feedback questions.

4.4.1. Expert selection

As already mentioned, non-response was one of the biggest concerns before sending out the survey. In order to increase the target group and the number of responses, the condition of "substantial knowledge of a certain field" was relaxed. This translated to assuming that having knowledge in the PI would enough to consider a candidate as knowledgeable in ports. Potential candidates were identified from online publications and workshops (i.e. SENSE or IPIC) related to the PI. The author decided to contact, two weeks before sending out the final survey, potential candidates that met the first condition. They were briefly presented with the purpose of the survey, the role participants needed to play, and finally asked for availability. Those who did not clearly state an unwillingness to participate in the survey would be considered as suitable candidates. Skepticism was visible from some of the subjects, with comments such as "my time is limited" or "how long will it take?". This gave an indication that the information presented in the survey, and the survey itself, would have to be as clear and concise as possible, so that the fatigue factor could be mitigated as much as possible.

In total, 78 subjects were identified as suitable candidates. 33 work in universities, while the remaining 45 come from industry. The majority of the candidates were located in Europe (72), and belonged to both academia (27) and industry (45). The other 6 candidates, all from academia, were located in North America (5 in USA and 1 in Canada). Up to 25 members of the SENSE project were identified within the European group. From these, 5 belonged to academia and the remaining 20 to industry.

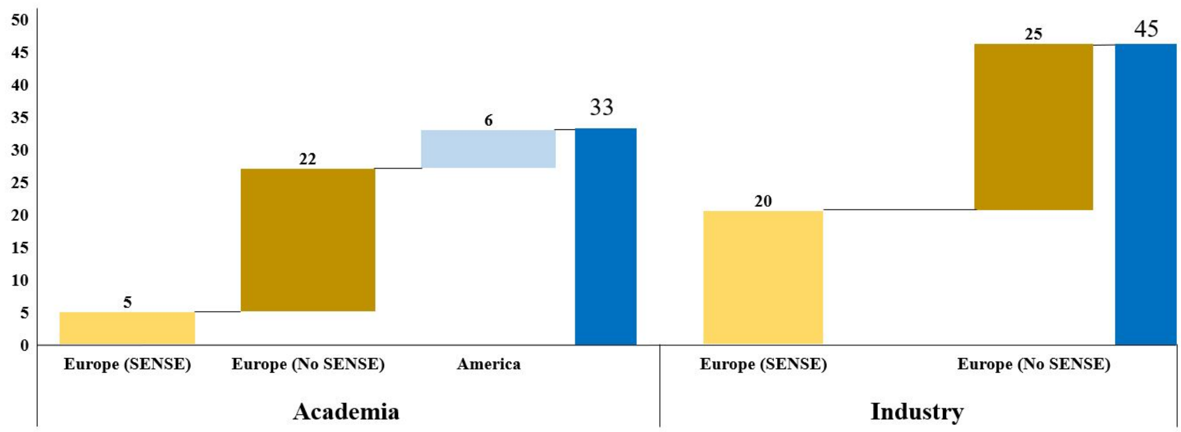


Figure 4.3: Characterization of potential candidates based on sector and geographical location.

4.4.2. Chosen tool for the Delphi

Since candidates were located geographically apart, and online tool had to be used, and for time reasons, the selection had to be done quickly. The platform typeform® was found to be a suitable tool to conduct the questionnaire. The main reason was its user-friendly interface for the participants, and the simple mechanism to send it to geographically dispersed experts. Its major drawback was its rigidity. It did not allow for communication in real time between the panel members and the author of this thesis. Therefore, potential misunderstandings, especially during the first round, could not be solved. Moreover, the length of the description of each of the four contextual scenarios was limited to the size of the interface. The following section explains how the questionnaire was designed, with the fatigue factor in mind.

4.4.3. Structure of the questionnaire

As already mentioned in Section 4.4.1, non-response was one of the biggest concerns before sending out the survey to the experts. Fatigue plays an important role, and therefore the questionnaire had to be designed in such a way that participants would not consider it too lengthy. The structure of both rounds are explained below.

Round 1

A total of 25 slides were the result of several iterations, were the experts could at last provide 2 answers per slide (one for 2030 and one for 2040, per dimension). With this format, fatigue could be kept low without decreasing the quality of the Delphi study. Round 1 was structured as follows:

1. A first welcome slide reminding the experts that the survey would take between 15 and 25 minutes. Although the aim from the author was less than 30 (see Section 2.4), a lower time was displayed to them to avoid discouraging experts to complete the survey.
2. 3 slides explaining the purpose of the survey, the PI Port framework, outlined in the previous Chapter 3 of this thesis, and the task of the participants, respectively.
3. A description of the first contextual scenario [see Appendix E], which was followed by 3 slides, each with a multiple-choice question for each of the 3 dimensions of the PI Port framework, respectively. Experts had to choose the level (from Current State to Level 4) that each dimension would reach for the years 2030 and 2040, as in a five-point scale [see Figure 4.3]. This process was repeated for the other 3 scenarios, completing a total of 12 slides to select 24 levels of development in total. To ease processing of the results and save the experts as much time as possible, there were not asked to argument each of their answers.
4. One slide with a multiple-choice question ("yes/no") asking whether they agreed on the two periods of time. If the answer was "no", the survey redirected them to a new slide where they could give their reasons.
5. One final open question asking for feedback about the PI Port framework.
6. A closing slide thanking the experts for participating in the survey. At this point, a reminder was send that a second and last round would be sent within the following weeks.

Since the chosen experts had to grasp in a short amount of time months worth of research, a short summary of the entire thesis was attached with the link to the survey [see Appendix F]. The purpose of the research, as well as how the author came up with the PI Port framework of Chapter 3, were provided in the summary to ease comprehension.

From Section 1.3.2, it was discussed from literature that the evolution of a port should be continuous, instead of evolving in discrete steps (Lee & Lam, 2016). For that reason, there could be the case that a particular PI dimension reaches half way between two distinct levels from the PI Port framework. Allowing experts to select intermediate levels would have given complexity to the Delphi, and eventually make it tiring in terms of length of the survey. To avoid falling into the already mentioned discrete and rigid "generations", while at the same time keeping fatigue as low as possible, the author decided to translate the categorical results of the panellists from fixed levels to quantitative values, from 1 (Current State) to 5 (Level 4). In-between ratios could give further interpretations to the results, as will be explained in Section 4.4.4.

Round 2

This second round kept a similar structure as Round 1, but reduced to 23 slides by removing redundant explanations at the beginning. For each multiple-choice question regarding the level that each dimension would reach for 2030 and 2040, the average responses from the previous round was provided [see Figure 4.4 (b)]. This was done in line with the fundamental rational of the Delphi method, with the hope that the feedback of the statistical group response would lead to consensus among the experts' opinions. Because of the limitations of the tool, each expert could not be reminded individually, during Round 2, about their personal answers from Round 1. This means they could not directly see how much their answers deviated from the group response, and therefore individual consistency could not be checked. The author decided at this point to assess group consistency instead, by checking whether the mode remained at the same category between both rounds.

Lastly, as mentioned at the end of Section 4.2, the hypothesis about the level of detail of the scenarios was tested in the Round 2 by asking the experts at the end whether they considered these had enough information to complete the questionnaire. Lastly, a feedback question about the Delphi methodology in general allowed the panellists to give their general opinion [see Appendix H].

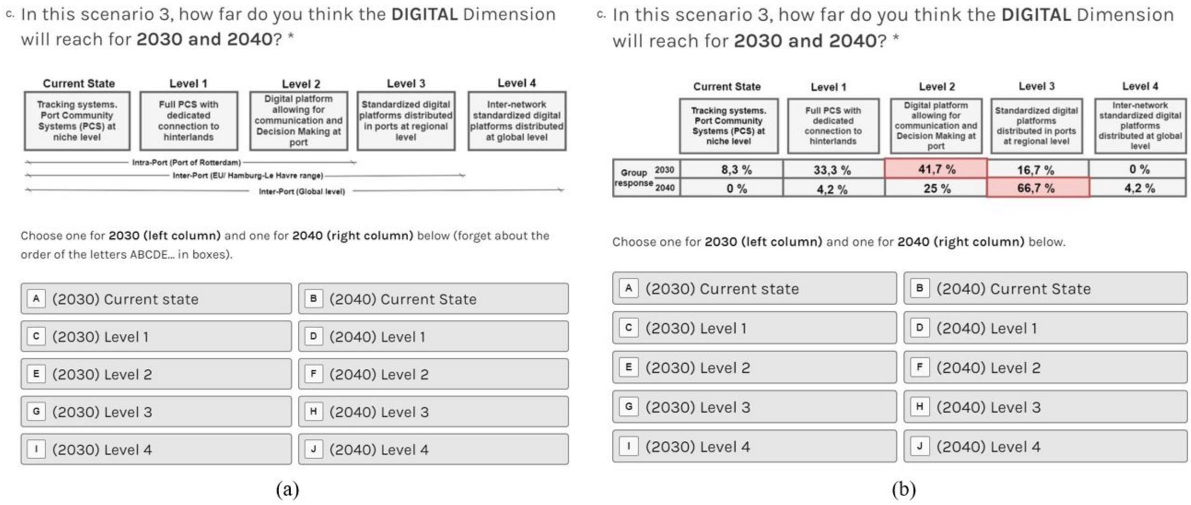


Figure 4.4: Example of online interface for both Round 1 (a) and Round 2 (b) of the Delphi survey. Red cells represent the categories with the highest percentages of votes per question (mode) from Round 1. Online Tool: typeform®.

4.4.4. Delphi Results

In total it took, including in-between round processing, 6 weeks to conduct the entire Delphi study approximately, which matches with the 45-day threshold proposed by Hsu and Sandford (2007). The Delphi results are outlined in this section.

Response rate

The average time to complete Round 1 by the experts was 14 minutes and 36 seconds, while for Round 2 it was 14 minutes and 33 seconds. This is less than the 30 minute threshold that the author aimed for. Out of the 78 panellists identified, 24 answered Round 1 and 20 answered Round 2. This is above the 12-member limit proposed in Chapter 2, and for that reason the author considers that the response rate has been high enough.

Group results

Figure 4.5 summarizes the group response from all the experts, for both rounds. The green, blue and grey colors represent the questions, for both 2030 and 2040, regarding the "Governance", "Operational", and "Digital" dimensions, respectively. For all the 24 categorical questions, the level that had the highest percentage of votes (mode) is coloured in orange.

Question	SCENARIOS		ROUND 1					ROUND 2				
SCENARIO 1			Current State	Level 1	Level 2	Level 3	Level 4	Current State	Level 1	Level 2	Level 3	Level 4
1	Governance	2030	12,5%	8,3%	**58,3%**	20,8%	0,0%	0,0%	30,0%	**60,0%**	10,0%	0,0%
2		2040	0,0%	8,3%	8,3%	**58,3%**	25,0%	5,0%	0,0%	20,0%	**65,0%**	10,0%
3	Operational	2030	8,3%	16,7%	**66,7%**	8,3%	0,0%	0,0%	15,0%	**65,0%**	20,0%	0,0%
4		2040	0,0%	4,2%	8,3%	**66,7%**	20,8%	0,0%	10,0%	0,0%	**75,0%**	15,0%
5	Digital	2030	8,3%	12,5%	**45,8%**	33,3%	0,0%	0,0%	0,0%	**70,0%**	30,0%	0,0%
6		2040	0,0%	4,2%	12,5%	29,1%	**54,2%**	0,0%	10,0%	0,0%	35,0%	**55,0%**
SCENARIO 2			Current State	Level 1	Level 2	Level 3	Level 4	Current State	Level 1	Level 2	Level 3	Level 4
7	Governance	2030	25,0%	**41,7%**	29,2%	4,2%	0,0%	25,0%	**50,0%**	25,0%	0,0%	0,0%
8		2040	4,2%	25,0%	**41,6%**	29,2%	0,0%	10,0%	25,0%	**55,0%**	10,0%	0,0%
9	Operational	2030	12,5%	16,7%	**54,2%**	16,7%	0,0%	5,0%	25,0%	**70,0%**	0,0%	0,0%
10		2040	0,0%	8,3%	33,3%	**37,5%**	20,8%	0,0%	10,0%	35,0%	**55,0%**	0,0%
11	Digital	2030	12,5%	16,7%	**54,1%**	16,7%	0,0%	0,0%	10,0%	**80,0%**	10,0%	0,0%
12		2040	0,0%	16,7%	25,0%	**45,8%**	12,5%	5,0%	5,0%	20,0%	**65,0%**	5,0%
SCENARIO 3			Current State	Level 1	Level 2	Level 3	Level 4	Current State	Level 1	Level 2	Level 3	Level 4
13	Governance	2030	**37,5%**	25,0%	**37,5%**	0,0%	0,0%	30,0%	**55,0%**	**10,0%**	5,0%	0,0%
14		2040	8,3%	25,0%	**37,5%**	29,2%	0,0%	10,0%	30,0%	**60,0%**	0,0%	0,0%
15	Operational	2030	12,5%	37,5%	**41,7%**	8,3%	0,0%	10,0%	30,0%	**55,0%**	5,0%	0,0%
16		2040	0,0%	12,5%	**45,8%**	37,5%	4,2%	5,0%	15,0%	**55,0%**	25,0%	0,0%
17	Digital	2030	8,3%	33,3%	**41,7%**	16,7%	0,0%	5,0%	5,0%	**75,0%**	15,0%	0,0%
18		2040	0,0%	4,2%	25,0%	**66,7%**	4,2%	0,0%	10,0%	20,0%	**70,0%**	0,0%
SCENARIO 4			Current State	Level 1	Level 2	Level 3	Level 4	Current State	Level 1	Level 2	Level 3	Level 4
19	Governance	2030	**37,5%**	33,3%	29,2%	0,0%	0,0%	**55,0%**	35,0%	5,0%	5,0%	0,0%
20		2040	12,5%	33,3%	**45,8%**	8,3%	0,0%	10,0%	**60,0%**	30,0%	0,0%	0,0%
21	Operational	2030	20,8%	**37,5%**	33,3%	8,3%	0,0%	15,0%	**50,0%**	35,0%	0,0%	0,0%
22		2040	4,2%	20,8%	**41,7%**	29,2%	4,2%	5,0%	25,0%	**60,0%**	10,0%	0,0%
23	Digital	2030	20,8%	**41,7%**	37,5%	0,0%	0,0%	10,0%	**55,0%**	35,0%	0,0%	0,0%
24		2040	8,2%	12,5%	**41,7%**	37,5%	0,0%	0,0%	25,0%	**50,0%**	25,0%	0,0%

Figure 4.5: Group response from the two Delphi rounds. The cell with the highest percentage of votes (mode) in orange, for each question.

Most votes generally feel on Level 2, with the highest evolution being reached in Scenario 1 for the "Digital Dimension", and with the lowest evolution in Scenario 4 in the "Governance Dimension". This suggests that optimism in the evolution of the PI was higher in Scenario 1 than in Scenario 4, with Scenarios 2 and 3 falling somewhere in between. Moreover, for Round 1, the percentages at the mode were generally higher in Scenario 1 than in the others, suggesting that, in the absence of feedback from other respondents, panellists initially agreed more in Scenario 1 than in the rest. Section 4.5 will further elaborate on this results, where the evolution path of the PI Port based on the evolution of the three PI dimensions will be outlined.

Consensus

To check consensus, the interquartile range (IQR) and the percentage of votes at the mode (now referred to as p[mode]), from the previous figure, are shown in Table 4.4. The values of IQR or p[mode] are in parenthesis whenever they do not reach the limits established by the consensus criteria, which is the case of 16 questions in Round 1. It is interesting to see how the remaining 8 are distributed along the four scenarios, with a decreasing number from Scenario 1 until Scenario 4. For the first scenario, 5 out of 6 questions meet the consensus criteria. In Scenario 2, only 2 out of 6 questions reached consensus. This decreasing tendency continues in Scenarios 3 and 4, where in the former, only one question meets consensus, and in the later none of the questions reached consensus. Breaking down the 16 questions where panellists did not agree, 6 belong to the "Governance Dimensions", while the remaining 10 are equally distributed among the "Operational Dimension" and the "Digital Dimension". The lowest level of consensus was found in question 13, were besides an IQR of 2, the maximum percentage of votes (37%, well below the 50% threshold) fell on two non-adjacent categories (Current State and Level 2).

The mode remained at the same category between both rounds for all questions, with the exception again of question 13, where the highest percentage of votes initially fell on two categories, and question 20. In fact, in all cases, the percentage of votes at the mode (p[mode]) increased in Round 2. These suggest that the group answers were somewhat consistent with respect to the first round. In line with the fundamental rational of the Delphi method, convergence generally increased in Round 2, with all questions meeting the consensus criteria adopted in this research (IQR≤1 and p[mode]≥50). In line with this, as it was already mentioned in Section 4.4.3, by assigning a quantitative value to each level, the mean and standard deviation could be computed for each question. These give further room for interpretation of the results. The standard deviation, as another indicator of convergence, decreased in all 16 questions were consensus was not initially reached. The largest increase in convergence was in question 5, with a reduction in standard deviation of 48,4%. An interesting finding is that increases in standard deviations, or decreases in convergence, albeit small (no more than 9.5% from question 4) occurred in the year 2040 only, which was the case for the three PI dimensions. It seems that experts could have been more influenced in their initial decision for year 2030 than for the year 2040, a point where the participants might have had a stronger opinion. This could perhaps be explained by the already mentioned "anchoring" effects, where experts envision the level of developments for the year 2040 and from there extrapolate backwards to the year 2030.

Table 4.4: Delphi statistics: mean, standard deviation and illustration of convergence among experts between both rounds.

Questions	Round 1 (n = 24) ART: 14,36 min					Round 2 (n = 20) ART: 14,33 min						
	IQR	p[mode]	mode	Mean	SD	IQR	p[mode]	mode	Mean	SD	$\Delta Mean$	ΔSD
Scenario 1												
1 Governance (2030)	0	58,3%	L2	2,87	0,88	1	60,0%	L2	2,8	0,60	-2,6%	-31,9%
2 Governance (2040)	0,25	58,3%	L3	4	0,82	0,25	65,0%	L3	3,75	0,83	-6,3%	1,6%
3 Operational (2030)	0,25	66,7%	L2	2,75	0,72	0	65,0%	L2	3,05	0,59	10,9%	-18,3%
4 Operational (2040)	0	66,7%	L3	4,04	0,68	0	75,0%	L3	3,95	0,74	-2,3%	9,5%
5 Digital (2030)	1	(45,8%)	L2	3,04	0,89	1	70,0%	L2	3,33	0,46	8,5%	-48,4%
6 Digital (2040)	1	54,2%	L4	4,33	0,85	1	55,5%	L4	4,35	0,91	0,4%	7,0%
Scenario 2												
7 Governance (2030)	(1,25)	(41,7%)	L1	2,12	0,83	0,5	50,0%	L1	2	0,71	-5,9%	-15,0%
8 Governance (2040)	(2)	(41,7%)	L2	2,95	0,84	1	55,0%	L2	2,65	0,79	-10,4%	-5,8%
9 Operational (2030)	1	54,2%	L2	2,75	0,88	0	70,0%	L2	2,65	0,57	-3,6%	-34,8%
10 Operational (2040)	1	(37,5%)	L3	3,70	0,89	1	55,0%	L3	3,45	0,67	-7,0%	-24,7%
11 Digital (2030)	1	54,1%	L2	2,75	0,88	0	80,0%	L2	3	0,45	9,1%	-49,1%
12 Digital (2040)	1	(45,8%)	L3	3,54	0,91	1	65,0%	L3	3,6	0,86	1,6%	-5,7%
Scenario 3												
13 Governance (2030)	(2)	(37,5%)	CS/L2	2	0,87	1	55,0%	L1	1,9	0,77	-5,0%	-11,3%
14 Governance (2040)	(2)	(37,5%)	L2	2,87	0,93	1	60,0%	L2	2,5	0,67	-13,0%	-27,6%
15 Operational (2030)	1	(41,7%)	L2	2,46	0,82	1	55,0%	L2	2,55	0,74	3,7%	-9,3%
16 Operational (2040)	1	(45,8%)	L2	3,33	0,75	1	55,0%	L2	3	0,77	-10,0%	3,9%
17 Digital (2030)	1	(41,7%)	L2	2,66	0,85	0	75,0%	L2	3	0,63	12,5%	-25,6%
18 Digital (2040)	1	66,7%	L3	3,70	0,61	1	70,0%	L3	3,6	0,66	-2,9%	8,6%
Scenario 4												
19 Governance (2030)	(2)	37,5%	CS	1,91	0,81	1	55,0%	CS	1,6	0,80	-16,5%	-1,5%
20 Governance (2040)	1	(45,8%)	L2	2,5	0,82	1	60,0%	L1	2,2	0,60	-12,0%	-26,5%
21 Operational (2030)	1	(37,5%)	L1	2,29	0,89	1	50,0%	L1	2,2	0,68	-4,0%	-23,7%
22 Operational (2040)	(1,25)	41,7%	L2	3,08	0,91	1	60,0%	L2	2,75	0,70	-10,8%	-23,2%
23 Digital (2030)	1	(41,7%)	L1	2,16	0,75	1	55,0%	L1	2,25	0,62	3,8%	-16,5%
24 Digital (2040)	1	(41,7%)	L2	3,08	0,91	0,5	50,0%	L2	3	0,71	-2,7%	-22,2%

Level	Current State (CS)	Level 1 (L1)	Level 2 (L2)	Level 3 (L3)	Level 4 (L4)
Eq. value	1	2	3	4	5

n: number of respondents
ART: Average Response Time
SD: Standard Deviation
IQR: Interquartile Range

Considering the group consistency and the consensus reached in all questions after two rounds, the results of the Delphi study can be considered as valid. The mean and mode are further used in Section 4.5 to define the evolution path of the PI Port for each of the 4 contextual scenarios.

Feedback on the two periods of time
There was almost complete consensus regarding the use of two periods of time. With the question stated as *"Do you think it was a good idea to include two points in time (2030 and 2040)?"* at the end of Round 1, the experts were given two options to select: "Yes, two points were good, since it allows to visualize a time path of the PI dimensions"; and "no". The purpose of adding two points in time was indeed to visualize a time path, and for that reason this was remarked in the first answer. 95,3% of respondents selected the first answer. Those who disagreed could freely reason their choice, which mainly referred to the difficulty to visualize the evolution path [see Appendix H for all answers].

Feedback on the PI Port framework
Also asked as an open question at the end of Round 1, experts were given the chance to provide their opinion about the resulting framework from Chapter 3. The question was formulated as *"Any comments on the conceptualization of the PI Port proposed in this survey?"*, and was answered by 45% of the participants. Given the free format of the answer, feedback covered different levels of abstraction without a clear direction. Some of the following however can be highlighted:

- The framework from Chapter 3 fixed the ordering of the cells, for each of the PI dimensions and the level of "port connectivity". This fixed structure was subject to feedback from some of the experts. For instance, some considered that "sometimes it seems easier to achieve Level 2 than Level 1", suggesting that vertical and horizontal integration might not always follow the same sequential order. Instead, these two processes, both at port level or network level, might develop in parallel. In line with this, particular feedback was given between the order of Levels 1 and 2 at the "Operational Dimension", where more than one expert shared the idea that "cross-docking and reshuffling of operations might occur earlier than true operational synchromodality". Moreover, other experts stated that a "further evolution levels between 3 and 4 could be useful", since the gap between the EU level to global networks might be too high to envision in the proposed period of time.
- For several experts, the governance seems to be the "most difficult to tackle for achieving the envisaged progress levels". In this sense, a "prioritization scheme", which shows the importance of some PI dimensions over the others, was advised. One expert however was "surprised by the high focus on regulations", stating that the "general culture in maritime ports and various competitive pressures influence decision making in this environment more than regulation."
- A few experts argued that the framework missed important elements. Some responses proposed to "consider an open dialog between ports and port cities", as well as "views for achieving a safer, securer, more efficient and low carbon footprint port and port cities" within the conceptual framework. Others missed the "data perspective", which is "the source to optimize decisions by algorithms". Albeit having considered the later throughout Chapter 3, the feedback suggest that the 2-page summary of the thesis attached to the first round, which briefly summarizes the framework, as well as the cells that correspond to the digital dimension, might have been oversimplified. As already explained, the fatigue factor played a big role in the structuring of the Delphi.

All the complete anonymous answers from respondents can be found in Appendix H. Chapter 6 will reflect on these opinions, and together with the level of developments achieved for each scenario, propose further research regarding the PI Port framework.

Feedback on Scenario logic

Stated as *"Do you think the scenarios were detailed enough?"*, experts were given the chance to give their opinions about the detail of scenarios of the Delphi and the end of Round 2. 75% chose "yes", while 25% chose "no" [see Appendix H]. From the later, some focused on the framework instead, which overlaps with the previous question, again stating that the ordering of the cells might not be "convincing". Others suggested that there is dependency between regulatory frameworks and global integration, as the theoretical framework from Williamson (1998) suggests. This opposes to the author's view that the influence (or correlation) would be relatively low, as explained in Section 4.1.6, contrary to what some experts stated as a "strong link" between the two driving forces.

An important finding had to do with the inter-dependency of the three PI dimensions, which would violate a premise that the author hypothesized in the PI Port framework from Chapter 3. From the feedback, it seems that the three dimensions "are not independent and have different impacts on any future developments". This was already stated in the previous open feedback question, which suggest that, in the case that these two responses do not come from the same person, the "prioritization" scheme might indeed be needed.

Feedback on Delphi survey

Lastly, an open question was asked at the end of Round 2. It aimed to collect any other comment or opinion not given before concerning the Delphi survey. The question was stated as *"Any other comments on the Delphi methodology in general?"*, and 25% of participants responded the question.

From a purely methodological perspective, some experts missed additional information, such as the "arguments from other participants about why they opted for a certain choice", which was already acknowledged as a potential concern by the author prior to the Delphi. Other expert focused on a basic drawback of qualitative inputs on visions about the future, since "visionary opinions, even if they come from experts, are risky as a basis to build knowledge, because there is no possibility for validation". Yet, the expert further acknowledged that the outcomes might be interesting since they show the level of "skepticism (or optimism) of PI thinkers" [see Appendix H].

4.5. Evolution levels of the PI dimensions and port connectivity

The statistical results provided in the previous section can be visualized as evolution paths for the different PI dimensions and the port itself, for each scenario. Section 4.5.1 outlines the evolution path of each PI dimension, for each scenario, while Section 4.5.2 elaborates on the evolution path of the PI Port, as a function of the 3 PI dimensions, for each scenario.

4.5.1. Evolution levels of the PI Dimensions

Chapter 3 proposed a framework which shows how a port evolves towards a PI Port as a function of three distinct PI dimensions. These three were assumed to evolve independently. In this section, the evolution path of the three PI dimension, for each of the four contextual scenarios, are outlined.

The evolution path can be expressed in terms of the mean or the mode. The former is consistent with the categorical design of the framework and the Delphi study, where experts had to select categories. Nevertheless, because of its simplicity, the risk of overlap in the evolution path of two or more PI dimensions might be relevant. The use of means instead can give further room for analysis. The opinions of those experts who did not select the mode are included when taking ratios instead of categories. In line with this, interpretation between two levels can be included. A major drawback of adopting this second criteria could be that the mean might not be reflecting the true opinion of any expert. As an example, the mean could be 2,3 (between Levels 2 and 3 and closer to the former), whereas none of the participants might have thought of a development level of 2,3 for any of the PI dimensions. Acknowledging their advantages and disadvantages, the evolution paths of the three dimensions, for each contextual scenario, are plotted considering both the mean and the mode.

PI Scenario 1

The first contextual scenario was dominated by a favorable global institutional integration, where the rise of democracies expanded to developing countries by 2040. The globalization process was followed by the emerging of intra-regional supply chain demands or ´glocalization´. In line with this, major power blocks such as the EU had been able to set up regulatory frameworks that could quickly adapt to market changes. This had lead to significant technological adoptions, eventually opening room for new cooperative business models [see Appendix E]. It is reasonable to consider Scenario 1 as the most optimistic out of the four presented in the survey. This is indeed reflected in the outcome from the experts, where the different dimensions in PI Scenario 1 reached further levels than in the other three PI scenarios.

For the year 2030, the mode of the three dimensions is Level 2, meaning that the highest number of votes fell in this level. The use of ratios can give further interpretation of the results. Indeed, the mean suggest a hierarchical tendency for the year 2030, with the "Digital Dimension" evolving the fastest (3,30), the "Governance Dimension" evolving the slowest (2,80) and the "Operational Dimension" in between (3,05).

Table 4.5: Summary of evolution levels in PI Scenario 1, for both the criterion of ratios (mean) and categories (mode) respectively.

Criteria	μ (mean)			Mode		
T	Gov_1^T	Op_1^T	Dig_1^T	Gov_1^T	Op_1^T	Dig_1^T
2030	2,80	3,05	3,30	3 (L2)	3 (L2)	3 (L2)
2040	3,75	3,95	4,35	4 (L3)	4 (L3)	5 (L4)

During the second time period (2030 to 2040), the "Digital Dimension" continues evolving the fastest, reaching the highest level of development (Level 4) in terms of votes. Both the "Operational Dimension" and the "Governance Dimension" develop in parallel when the mode is considered. If the mean is considered instead, the "Digital Dimension" evolves the fastest and to the highest ratio (4,35), while the other two evolve relatively at a similar pace, with the "Operational Dimension" finishing in between (3,95) and the remaining dimension reaching 3,75. Figure 5.2 visually reflects how far each dimension reaches but also the pace at which they evolve.

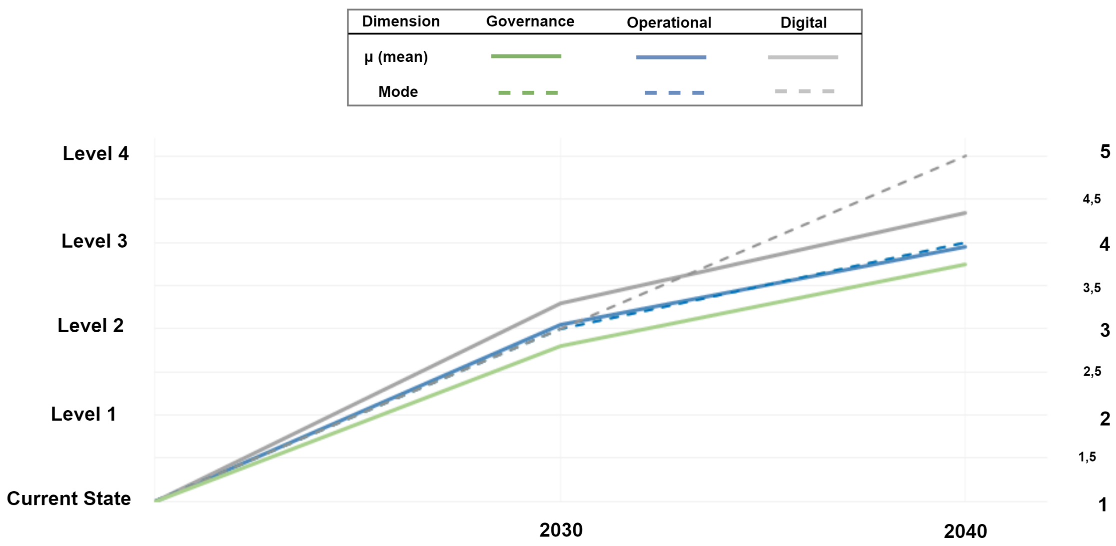


Figure 4.6: Development of the PI dimensions for PI Scenario 1.

PI Scenario 2

The second contextual scenario was also dominated by a favorable globalization context, with the rise of democracies expanding to developing countries by 2040 and eventually leading to the emerging the so-called "glocalization" process. Nevertheless, regulatory frameworks had lagged behind market developments, hindering the adoption of new technologies which could ease cooperative models. Given this description of the future, it would seem reasonable to expect PI Scenario 2 as less optimistic than the first PI scenario, but more optimistic than PI Scenario 4.

For the year 2030, the mode of both the "Digital Dimension" and the "Operational Dimension" is Level 2, whereas the "Governance Dimension" evolves up to Level 1 only. When computing the ratios, the evolution of the first and last dimension match with the mode. The "Operational Dimension", on the contrary, falls somewhere between Level 1 and Level 2, but closer to the later (2,65).

Table 4.6: Summary of evolution levels in PI Scenario 2, for both the criterion of ratios (mean) and categories (mode) respectively.

Criteria	μ (mean)			Mode		
T	Gov_1^T	Op_1^T	Dig_1^T	Gov_1^T	Op_1^T	Dig_1^T
2030	2,00	2,65	3,00	2 (L1)	3 (L2)	3 (L2)
2040	2,65	3,45	3,60	3 (L2)	4 (L3)	4 (L3)

During the second time period (2030-2040), the three dimensions evolve more slowly, with the "Digital Dimension" and the "Operational Dimension" equally reaching Level 3, and the "Governance Dimension" reaching Level 2 only. The mean allows to see differing evolution paths during this period, with the "Operational Dimension" evolving the fastest to 3,45, and the "Digital Dimension" and the "Governance Dimension" evolving somewhat at a similar pace, to 3,60 and 2,65 respectively.

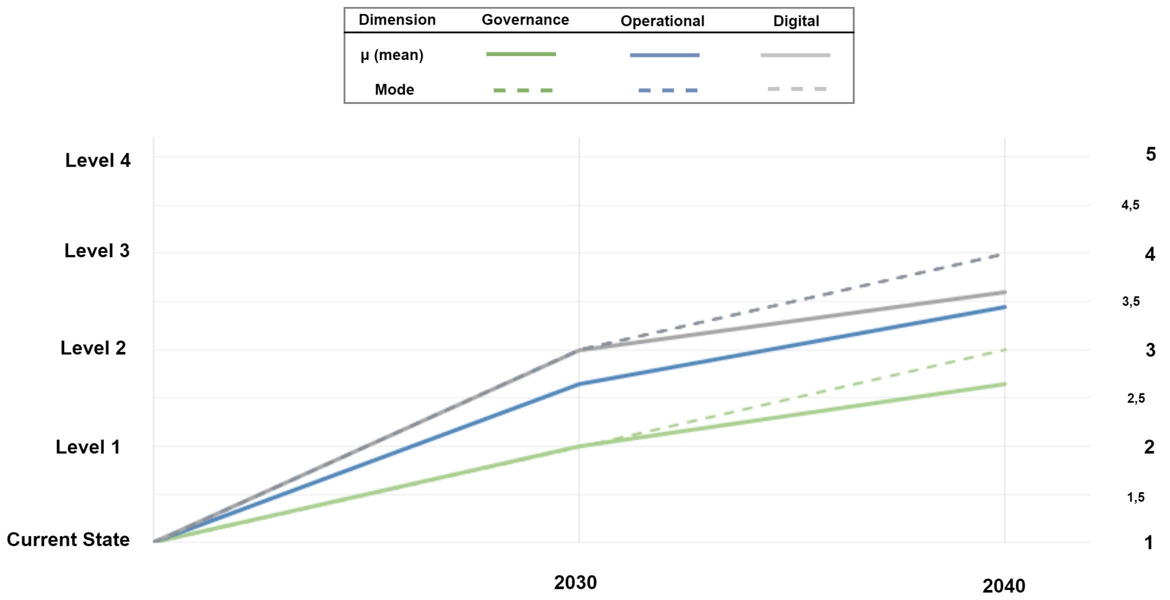


Figure 4.7: Development of the PI dimensions for PI Scenario 2.

PI Scenario 3

The third contextual scenario was dominated by a highly protectionist environment between major power blocks, such as between the US and the EU, which had slightly affected global maritime alliances. Internally, the European Union had been threatened by nationalistic movements, yet remaining successfully contended. Nevertheless, the EU had been able to set up regulatory frameworks that could quickly adapt to market changes. This had lead to moderate technological adoptions, eventually opening room for cooperative-based niches from which companies can further profit. This description of the future seems to translate to an evolution path similar to PI Scenario 2, less optimistic than PI Scenario 1 and more optimistic than PI Scenario 4.

In the year 2030, the "Governance", "Operational" and "Digital Dimension" reach Level 1, Level 2 and Level 2 respectively, just as in Scenario 2. When plotting the mean, the "Digital Dimension", evolves the fastest all the way to 3,00 [see Figure 5.4]. This is followed by the "Operational Dimension" and lastly by the "Governance Dimension", which evolve to 2,55 and 1,90 respectively.

Table 4.7: Summary of evolution levels in PI Scenario 3, for both the criterion of ratios (mean) and categories (mode) respectively.

Criteria	μ (mean)			Mode		
T	Gov_1^T	Op_1^T	Dig_1^T	Gov_1^T	Op_1^T	Dig_1^T
2030	1,90	2,55	3,00	2 (L1)	3 (L2)	3 (L2)
2040	2,50	3,00	3,60	3 (L2)	3 (L2)	4 (L3)

Within the second period, the "Digital Dimension" evolves to Level 3 and the "Governance Dimension, to Level 2. The "Operational Dimension" flattened and remained at Level 2. The mean can give further information on the evolution paths. The "Operational Dimension" evolved slightly slower than the other two, and reached exactly the value of 3,00. This is the equivalent of Level 2, which explains with the mode stagnated. Both the "Digital Dimension" and the "Governance Dimension" evolved at the same pace, reaching 3,60 and 2,50 respectively.

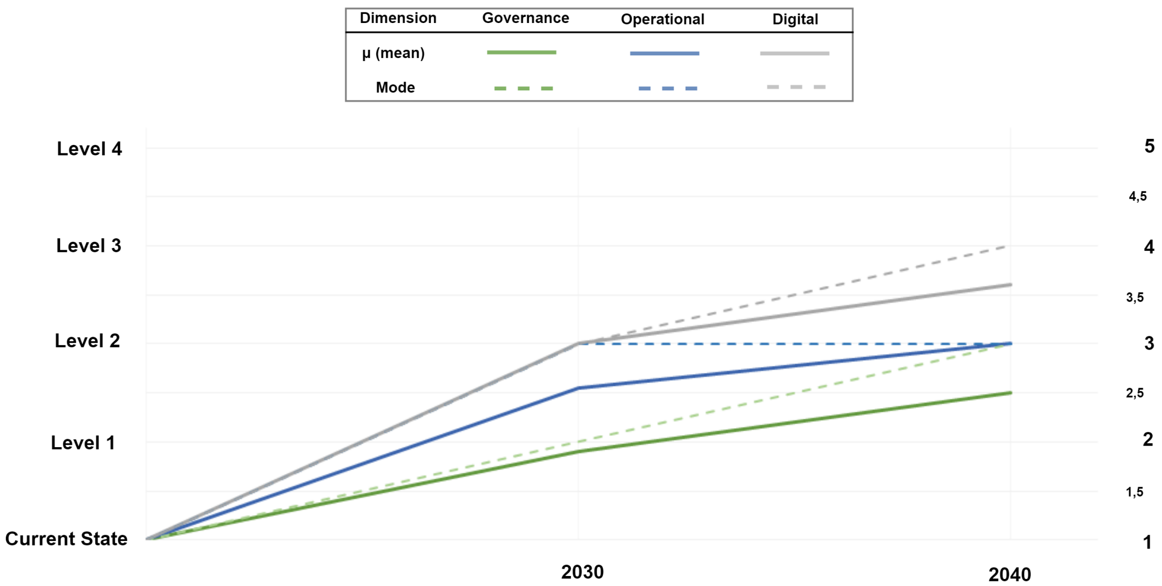


Figure 4.8: Development of the PI dimensions for Scenario 3.

PI Scenario 4

The fourth and last contextual scenario was dominated by a challenging environment both in terms of global institutional integration and regulatory frameworks. Protectionism had risen between the major power blocks, and at the regional level, nationalistic movements had threatened the European Union project, although the later had remained contended. Moreover, regulatory frameworks have lagged behind market developments, limiting newer technological adoptions to the biggest players, such as the maritime alliances that are known nowadays. Based on this description, is would be reasonable to expect Scenario 4 as the most pessimistic out of the four presented in the survey. This unfavorable external environment was translated by the experts into lower levels of development of the different PI dimension than in the other three PI scenarios.

For the year 2030, the three dimensions reached different levels. For both the "Digital Dimension" and the "Operational Dimension", most of the votes fell in Level 1, while the "Governance Dimension" lagged behind and the mode remained at the Current State. When looking into the mean, both the former two dimensions evolved almost at the same pace (2,20 and 2,25 respectively), fairly surpassing the Level 1 threshold. The slowest layer reached half way between the Current State and Level 1 (1,60).

Table 4.8: Summary of evolution levels in PI Scenario 4, for both the criterion of ratios (mean) and categories (mode) respectively.

Criteria	μ (mean)			Mode		
T	Gov_1^T	Op_1^T	Dig_1^T	Gov_1^T	Op_1^T	Dig_1^T
2030	1,60	2,20	2,25	1 (CS)	2 (L1)	2 (L1)
2040	2,20	2,75	3,00	2 (L1)	3 (L2)	3 (L2)

During the second time period (2030 to 2040), the "Digital Dimension" once again evolved the fastest [grey continuous line in Figure 5.5], reaching exactly Level 3 in terms of votes, as the case of the "Operational Dimension", and mean. The "Governance Dimension" evolved faster than the previous, yet the mode remained at Level 2, with the mean at 2,20 [green continuous line in Figure 5.5], fairly lower than the other two PI layers.

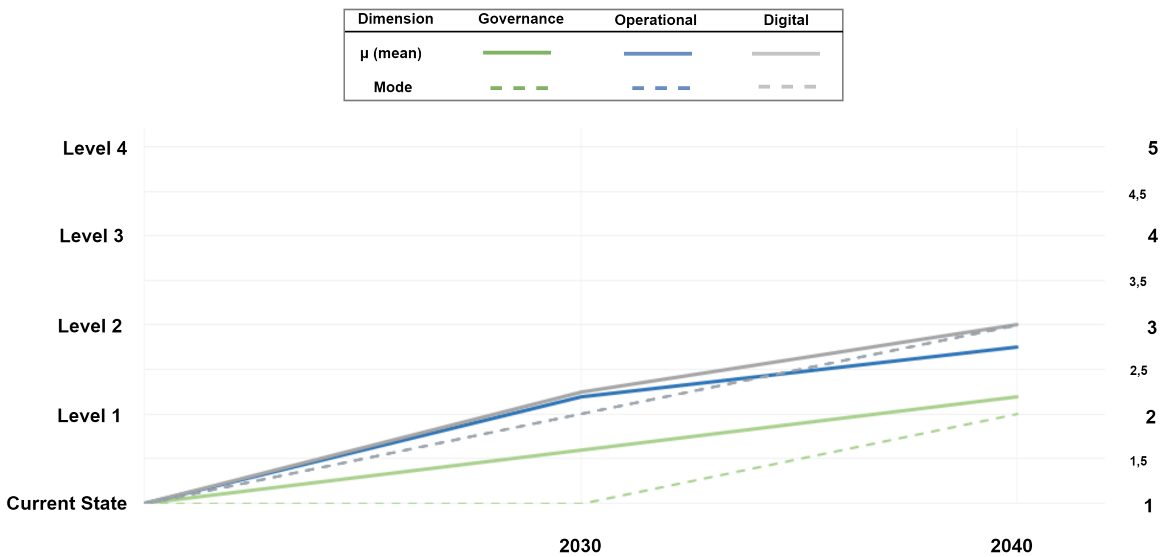


Figure 4.9: Development of the PI dimensions for PI Scenario 4.

4.5.2. Evolution path of port connectivity

As already mentioned, Chapter 3 proposed a framework that shows how a port evolves towards a PI Port as a function of the evolution of three distinct PI dimensions. Each cell of the port connectivity would jump upward one level whenever the three PI dimensions had done so. In other words, for a particular point in time, the level of port connectivity is never greater than the level that any of the three PI dimensions reach. Referred to as $PI^T_{Port,i}$ in the following mathematical relationship, the level of port connectivity is therefore defined as the *minimum level of the three PI dimensions, for each point in time and each PI scenario.*

$$PI^T_{port,i} = min\{Gov^T_i; Op^T_i; Dig^T_i\}$$

where,

$PI^T_{port,i}$	Level of port connectivity at year $T \in \{2030; 2040\}$ for PI scenario $i \in \{1;2;3;4\}$
Gov^T_i	Level that the "Government dimension" reaches at year T for PI scenario i
Op^T_i	Level that the "Operational dimension" reaches at year T for PI scenario i
Dig^T_i	Level that the "Digital dimension" reaches at year T for PI scenario i

The levels of development of each PI dimension, for each PI scenario, were computed in previous Section 4.5.1 in two ways. Firstly by using the mode, which was the category with the highest percentage of votes from the Delphi, and secondly by computing the mean. In this sense, the level of evolution of the port, for each point in time and PI scenario, can be defined by either the minimum of the three modes, or the minimum of the three means. Table 4.9 summarizes the results outlined in the previous section for all scenarios, and presents the evolution level that the port reaches. Values in the left column represent the mean value of the PI dimensions and "port connectivity" from 1 (Current State) to 5 (Level 4), while the right column represent the category with the highest percentage of votes (mode), for each question respectively.

Table 4.9: Summary of evolution levels of the port for all PI scenarios, for both the criterion of ratios (mean) and categories (mode) respectively.

Criteria		μ (mean)				Mode			
Dimension		Gov^T_i	Op^T_i	Dig^T_i	$PI^T_{port,i}$	Gov^T_i	Op^T_i	Dig^T_i	$PI^T_{port,i}$
PI Scenario 1	2030	2,80	3,05	3,30	**2,80**	3 (L2)	3 (L2)	3 (L2)	**3 (L2)**
	2040	3,75	3,95	4,35	**3,75**	4 (L3)	4 (L3)	5 (L4)	**4 (L3)**
PI Scenario 2	2030	2,00	2,65	3,00	**2,00**	2 (L1)	3 (L2)	3 (L2)	**2 (L1)**
	2040	2,65	3,65	3,60	**2,65**	3 (L2)	4 (L3)	4 (L3)	**3 (L2)**
PI Scenario 3	2030	1,90	2,55	3,00	**1,90**	2 (L1)	3 (L2)	3 (L2)	**2 (L1)**
	2040	2,50	3,00	3,60	**2,50**	3 (L2)	3 (L2)	4 (L3)	**3 (L2)**
PI Scenario 4	2030	1,60	2,20	2,25	**1,60**	1 (CS)	2 (L1)	2 (L1)	**1 (CS)**
	2040	2,20	2,75	3,00	**2,20**	2 (L1)	3 (L2)	3 (L2)	**2 (L1)**

Joining the values of 2020 (assumed to be the current state) with the evolution levels reached in 2030 and 2040, according to the previous table, allows to visualize an evolution path of port connectivity. The results for all PI scenarios are plotted in Figure 4.10, with continuous lines representing the mean and dashed lines representing the mode.

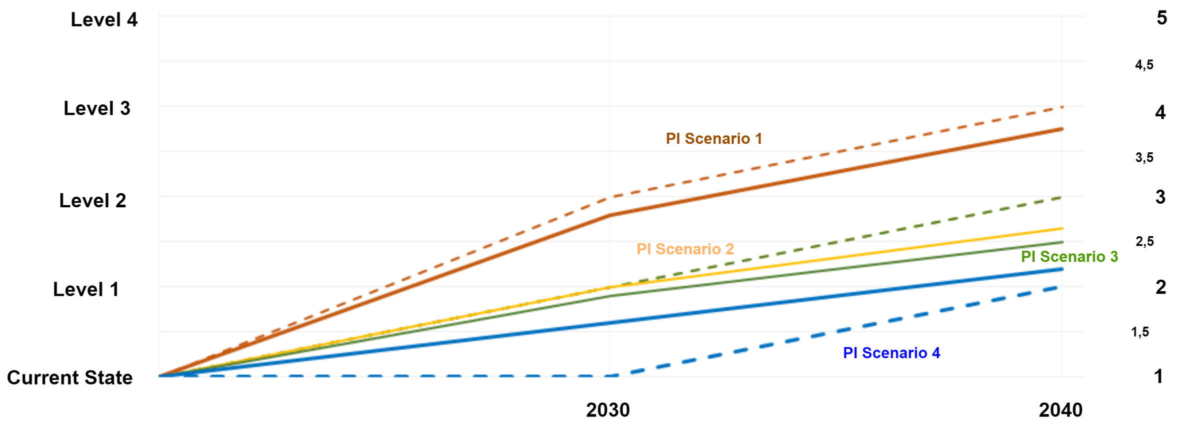


Figure 4.10: Evolution of port connectivity for each of the four PI scenarios for both the mean (continuous lines) and the mode (dashed lines).

PI Scenario 1

As expected, PI Scenario 1 was the most optimistic, with the fastest evolution path. The mode reaches Level 2 in the year 2030, which means achieving the so-called "Physical Intranet" of the entire port community from the PI Port framework [see Section 3.2.2]. This means that same segment terminals (i.e. ECT or APM Terminals for the case of the PoR) are open horizontally within the port and are also intensely connected within the three PI dimensions. Moreover, governing bodies, as well as inbound/outbound modes within the port are also intensely connected. For the year 2040, the mode 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 range if the PoR is considered. This could be seen as a form of "Physical Internet" at a regional (European) level.

The mean suggests a slightly lower evolution, with the "Physical Intranet" still under adoption for the year 2030, but highly advanced. This could translate to some stakeholders, from companies to governing bodies, still taking measures to become part of the intra-port interconnectivity. Similarly, for the year 2040, few ports are still to join the regional Physical Internet.

PI Scenario 4

On the other extreme lays PI Scenario 4. In this case, the mode 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 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 is still under way for the horizon year 2040.

PI Scenario 2 & 3
In between the two extreme cases lay PI Scenario 2 and PI Scenario 3, which evolve in similar evolution paths. In fact, the mode for both PI scenarios overlap completely during the entire time period considered, evolving to Level 1 and Level 2 for the years 2030 and 2040 respectively. This translates to a situation in which 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 Scenario 2 evolves slightly faster throughout the entire period than PI Scenario 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.

Conclusions from the results
From both Table 4.9 and Figure 4.10, several conclusions that can be drawn from the results.

- **From the PI scenarios it seems that the "Governance Dimension" is lagging behind, and adopting the minimization rule used in this section, this dimension would be the most critical out of the three PI dimensions.** This also reflects the opinions of some of the experts from the Delphi study, where it was stated that "digitalization is the easiest to achieve, operations is harder, but governance is extremely difficult".

- Looking again into the mean from PI Scenario 2 and PI Scenario 3, the combination of driving forces could have influenced respondents to assign, on average, a slightly higher pace of development during the first 10 years to PI Scenario 2 than to PI Scenario 3. The former encompassed a situation dominated by a favorable global institutional environment and slow regulatory frameworks, while the later described a future with opposite directions of the driving forces. In this sense, **it seems that experts, on average, penalized more an environment of high protectionism (from Scenario 3) than a future with regulatory frameworks lagging behind market developments (from Scenario 2).**

- Level 4 was the ultimate stage in the proposed framework from Section 3.2.2. Reaching this level would mean a full global roll-out of the Physical Internet, according to the formal definition given by B. Montreuil, Meller, and Ballot (2012), with maritime ports acting as PI hubs in a global hyperconnected network. Such level is never reached under any of the four scenarios considering the minimization rule. Looking into the results from the Delphi, **under the most optimistic scenario in terms of global institutional integration and regulatory frameworks (PI Scenario 1), the "Physical Internet" in ports as nodes of freight transport systems is achieved at the regional (European) level at most.** If different rules were considered to derive the evolution path of the port, such as a compensation between the three dimensions (i.e. average of the three), Level 4 would still not be reached. Only by using a maximization rule, with the "Digital Dimension" as a forerunner, PI Scenario 1 would reach close to the latest stage in terms of mean. The realism of this last criteria should however be subject to debate with experts in the field of PI.

4.6. Implications for the Port Authority of Rotterdam

The Research Objective of this thesis was to *"generate contextual scenarios that influence the development of a PI Port so that Port Authorities can consider such influence in their strategic policies and therefore adapt accordingly"*. Given the previously visualized results, this section concludes Chapter 4 and serves as a closing remark to the goal of the thesis, with the Port Authority of Rotterdam functioning as the problem owner.

Assuming that the goal of the Port Authority of Rotterdam, or any other port governing body, is to maximize the level of port connectivity from the PI Port framework for the projected years, the aim should be to maximize the minimum, or slowest, of the three dimensions, which was the rule adopted to derive the evolution paths. This would be equivalent to a Min-Max problem in mathematical jargon.

Given the particular results herein presented, **the author of this thesis recommends maritime ports to focus on the "Governance Dimension"**. This means bringing in together different stakeholders and engaging in a new set of rules needed for a cooperative, safe and reliable Physical Internet. Without the purpose to offer an exhaustive policy roadmap, and considering that ports evolve at different paces, the following could be highlighted to take into account by the Port of Rotterdam:

- **Evaluate and monitor the implementation of the Rotterdam Rules.** As explained in Section 3.2.2, its ratification and entry into force is a governmental decision and therefore out of the reach of the Port Authority of Rotterdam. What the Port Authority can do however, as a leading port in Europe, is play an advisory role with other stakeholders. This means evaluating and monitoring the progress state of its implementation in the Netherlands, neighboring countries within the Hamburg-Le Havre range, and the rest of Europe. By doing so, governments can be informed and work more closely together towards a parallel and joint implementation. In this sense, the Rotterdam Rules would be more effective when all countries together implemented them jointly.

- **Consortia Block Exemption Regulation.** Another important point deals with the decision under consultation to extend or expire, in April of 2020, the maritime "Consortia block Exemption Regulation" (CBER). The exemption allows maritime shipping lines to enter, under certain conditions, into cooperation agreements to provide joint cargo transport services. Two possibilities could be further studied at this point:

  - Promote the extension of the CBER. This would mean that shipping lines with a combined market share of below 30% could continue entering into cooperation agreements.
  - Bring in policy makers and other stakeholders (i.e. European port authorities and representatives from the shipping line industry) to discuss to replacement of the CBER for a new exemption that allows for even more flexible cooperation between carriers and nodes, including the hinterland, while still falling under the umbrella of Article 101 of the TFEU.

While the "Governance Dimension" seems to be the major bottleneck towards PI Ports, **the other two PI dimensions should not overlooked.** For both the "Operational Dimension" and the "Digital Dimension", an advisory role to other stakeholders, mainly other port authorities, could be played by the Port of Rotterdam.

Regarding the "Operational Dimension", the Port of Rotterdam is leading the path towards automated handling operations, with terminals and other port users investing significant efforts to improve their own operations. Albeit not being direct competence of the Port Authority, this body could promote other stakeholders, such as the terminals themselves, to share knowledge and experiences with other ports were automation of operations are lagging behind.

On the other hand, the Port of Rotterdam is one of the leading maritime ports in terms of digitalization. This is reflected in the so-called "Digital Maturity Model" (PoR.b, 2018) envisioned by the Port Authority, which develops a similar bottom-up approach as proposed in the PI Port framework of this thesis, yet focusing in the digital side only [See Appendix C]. Different levels are also proposed, and it scales from individual parties being connected within the port (Level 1) to the entire port community, the hinterland and eventually an integrated door-to-door digital logistics chain is created on a global scale (Level 4). The gap between the digitalization within the port and between ports globally is a big step, and it means that other ports would have to be following the same path towards digitalization. Nevertheless, as already mentioned in Chapter 1, "all ports are, to some extent, unique" (Beresford et al., 2004), meaning that not all ports will be at the same level of development, in the current state, as the Port of Rotterdam. Such divergence could eventually hinder the scaling of digitalization from local to regional or global level.

To facilitate convergence among ports in terms of digitalization, the Port of Rotterdam could play an advisory role with neighboring ports in Europe. Knowledge and expertise could be transferred, so that the current Port Community Systems (such as PortBase in the Netherlands) in different countries of the EU can scale up jointly and eventually converge into one regional distributed digital platform.

As can be seen, since the adoption of the Physical Internet entails all players within freight transport systems, the general recommendations derived in this section propose leading port authorities to look beyond their own physical domains. This means not only focusing on their hinterlands, as currently outlined in literature, but on other neighboring ports and promote their development. It was mentioned in Section 1.2.1 that "enhancing the competitive position of the port as a transport hub, in terms of volume and quality, is of upmost importance for the Port Authority of Rotterdam" (PoR, 2017). This is still compatible with the general recommendations derived in this section. Albeit at different paces depending on the international context, global trade increases in all four contextual scenarios presented in this thesis. The Port of Rotterdam and other neighboring ports can continue attracting more volume, while the former playing the advisory role mentioned so that the rest of stakeholders increase efforts towards connectivity at a regional level. This is, in essence, the cooperative philosophy of the Physical Internet.

5

Conclusion

From the gap identified in Chapter 1, the research goal of this thesis was formulated as follows:

Generate contextual scenarios that influence the development of a port into a PI port so that Port Authorities can consider such influence in their strategic policies and therefore adapt accordingly.

To fulfill this objective, the main Research Question (MRQ) was formulated as:

What are the scenarios for the development of maritime ports under the Physical Internet?

This research question was divided into different sub-questions. The purpose of this chapter is to answer the proposed sub-questions, which together can contribute to fill in an important research gap.

1. ***What are the main PI characteristics?*** *Chapter 3*

An in-depth literature review, followed by interviews, was conducted in Chapter 3 to derive the main PI characteristics. From both the 41 publications reviewed and the 4 consultations, there seems to be a lack of consensus regarding what the Physical Internet actually entails. Considering all the input from literature and the different levels of abstraction given by the experts, the identified characteristics from both sources were clustered into three distinct overall layers. **The main PI characteristics that were distinguished are the following:**

- **Operational dimension.** This dimension refers to how transport is physically executed and operated by the different elements in the transport network, from hubs, warehouses, vehicles or handling equipment.
- **Digital dimension.** This dimension deals with the digital connectivity of the different players in the logistics network. A system is in place so that the actors can share information, communicate with each other and make decision for optimized transport networks.
- **Governance dimension.** Businesses need rules and protocols in place for exchange of data, and goods within the Physical Internet, from individuals and smaller businesses to the bigger companies. The "Governance Dimension" refers to this set of rules for a cooperative, safe an reliable PI environment.

2. How do the main PI characteristics influence the evolution of maritime ports? *Chapter 3*

Based on the generalized characterization of the Physical Internet shown above, the same three characteristics were particularized to the context of maritime ports as nodes in freight transport systems. **The resulting framework**, from Chapter 3, **depicts a bottom-up approach in which the three PI characteristics or dimensions influence the evolution of what was referred to as "port connectivity".**

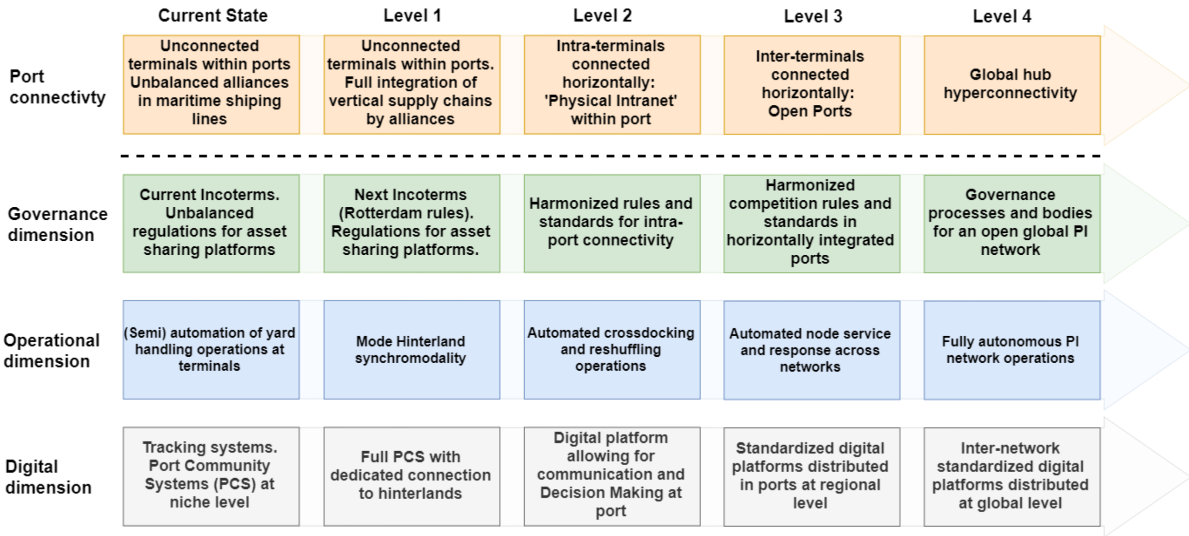


Figure 5.1: Resulting PI Port framework, with evolution levels on a categorical five-point scale.

Within the proposed "Governance Dimension", the current scattered standards and reactive Incoterm rules progressively evolve to the implementation of governance bodies for an open global PI network, which respect the sovereignty and integrity of the different nodes, ensuring seamless, secure and confidential exchange of data, goods and assets. Regarding the "Operational Dimension", semi automation of yard handling operations evolve over time into complete autonomous operations within the port domains, exploiting the benefits of open networks. Lastly, within the "Digital Dimension", current tracking systems at niche level evolve all the way to standardized digital platforms that allow for digital connectivity among different networks.

Each cell of "port connectivity" jumps upward one level whenever the three PI dimensions had done so. In other word, for a particular point in time, the level of port connectivity is never greater than the level that any of the three PI dimensions reach. In an ideal situation, each dimension evolves independently from their Current State up to Level 4. This framework was considered the "system" from which relevant driving forces would be selected, and therefore contextual scenarios would be constructed.

3. What are the main external factors affecting the PI characteristics and how? *Chapter 4*

The development of the different PI characteristics, which influence the evolution of port connectivity from the PI Port framework, are affected by external factors. From literature, reports, the conducted interviews, and brainstorming sessions, 32 final contextual factors which could potentially influence the PI characteristics were identified. Following the clustering into 7 driving forces, through logic reasoning, these were assessed according to their relevance on the "system", based on "impact" and "uncertainty". From the individual assessment of each of them, **the most relevant driving forces were "global institutional integration" and "regulatory frameworks".** Four contextual scenarios were presented as a combination of the opposing directions that the selected driving forces could take.

Driving Force	Impact	Uncertainty
Global institutional integration	**Large**	**Large**
Flow patterns	Small	Large
Climate change	Small	Small
Technological innovations	Large	Small
Regulatory frameworks	**Large**	**Large**
Business models	Small	Small
Demographic changes	Small	Small

To derive **how the main external factors (or driving forces) influenced the PI characteristics**, a Delphi study was conducted. The four contextual scenarios were used, together with the PI Port framework from Chapter 3, as input for a two-round Delphi survey with experts in the field of PI. The panellists had to select the level of development of each of the three PI dimension, for the years 2030 and 2040, and for each of the four scenarios, which totalled 24 questions per round, aside from the open feedback questions at the end of each session. Consensus, considered a desired goal for this Delphi study, was reached in all questions after the two rounds. The categorical results could outline an evolution path of the different PI dimensions based on their mode throughout the time period considered (PI Scenarios). Moreover, for further interpretation of the results, a quantitative value was assigned to each of the levels from the framework. Therefore, the mean was also outlined along with the mode. The following figures reflect the evolution path of the 3 PI characteristics for each contextual scenario. These are also called in this thesis "PI scenarios".

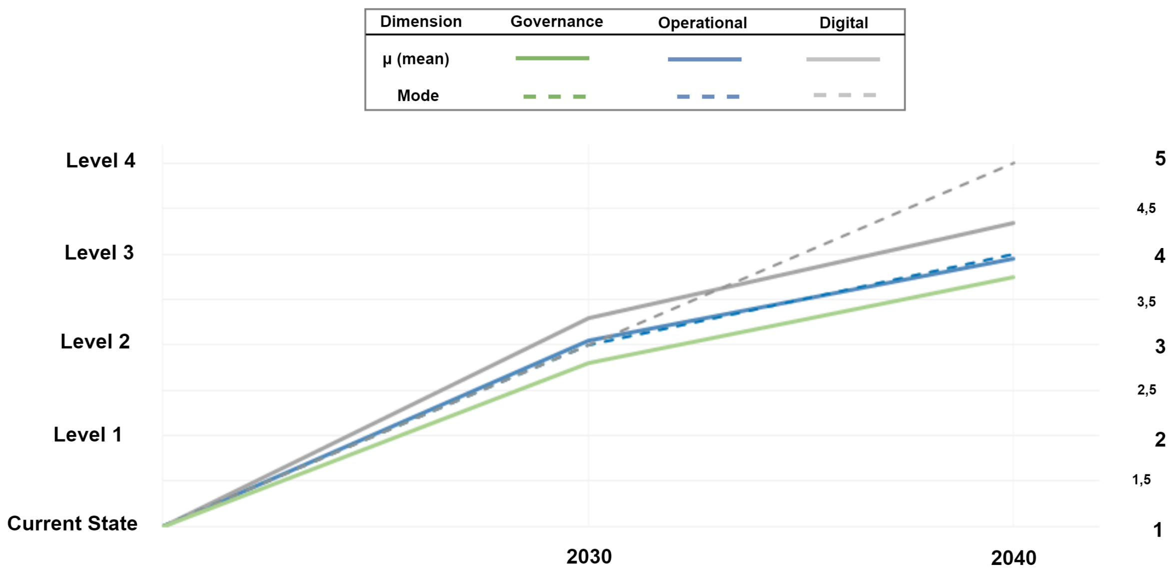


Figure 5.2: Development of the PI dimensions for PI Scenario 1.

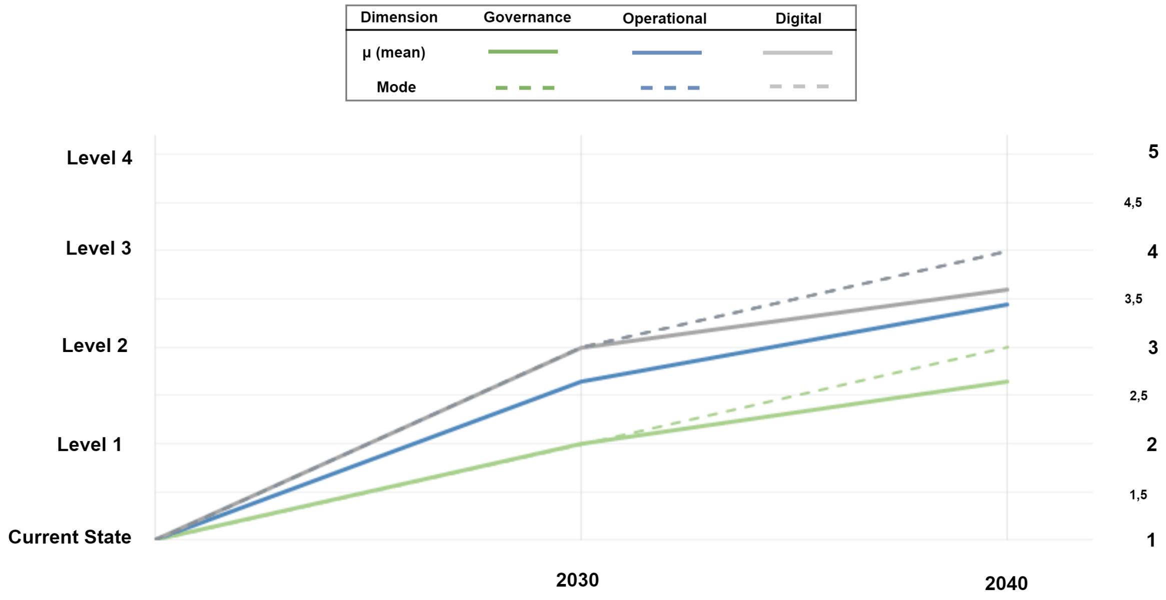


Figure 5.3: Development of the PI dimensions for PI Scenario 2.

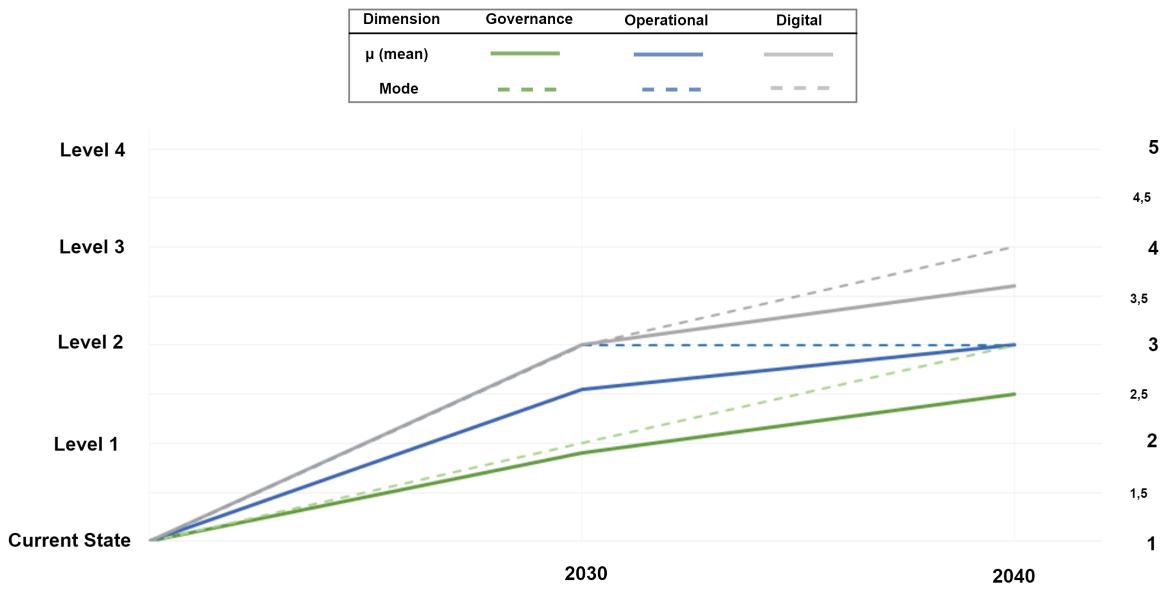


Figure 5.4: Development of the PI dimensions for Scenario 3.

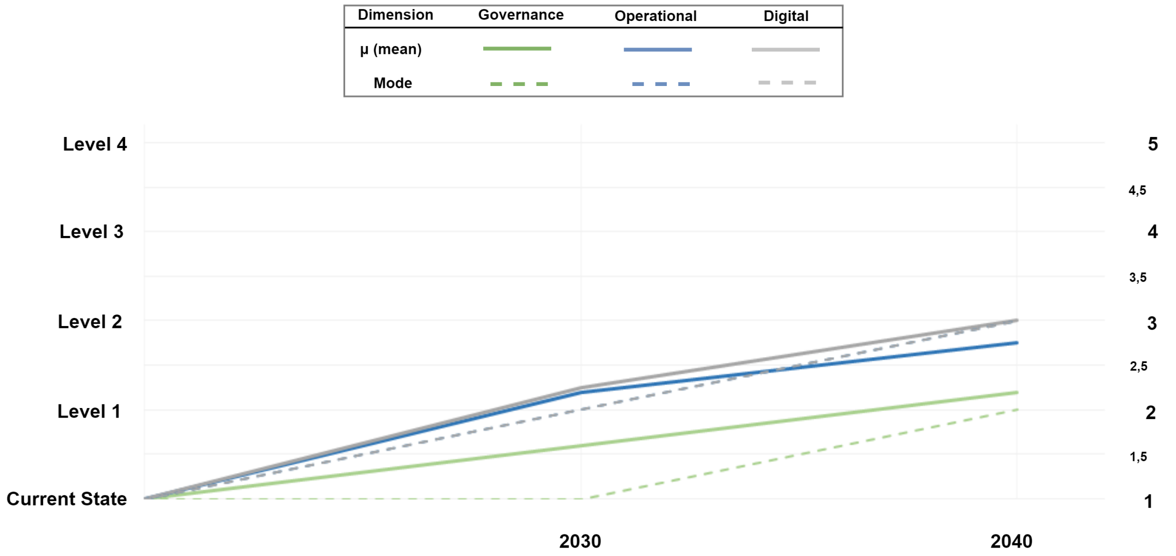


Figure 5.5: Development of the PI dimensions for PI Scenario 4.

4. How do maritime ports evolve for each scenario? *Chapter 4*

To derive how maritime ports evolve for each PI scenario, a minimization criteria from the three PI dimension was proposed. As a basis of "port connectivity", the results give the following evolution paths.

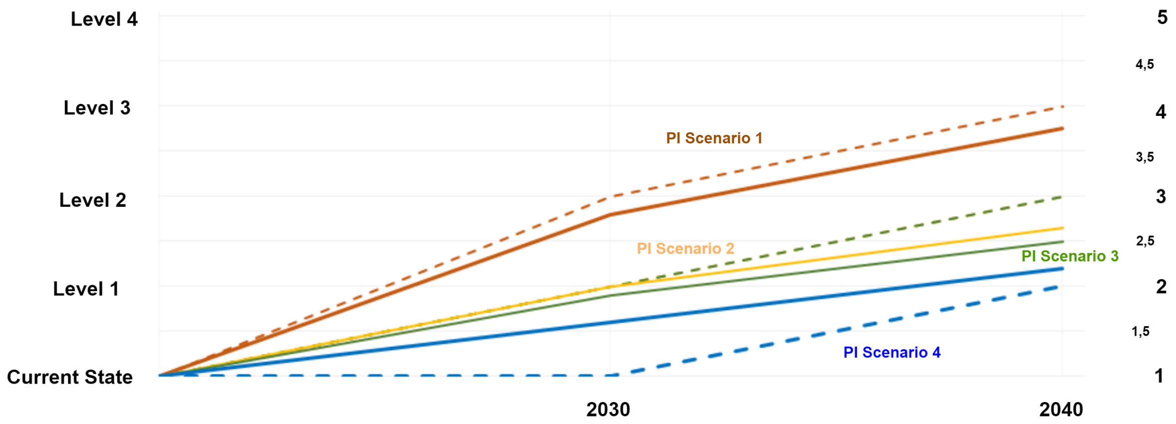


Figure 5.6: Evolution of "port connectivity" for each of the four PI scenarios, considering both the mean (continuous lines) and the mode (dashed lines).

PI Scenario 1

The most optimistic evolution path was reflected in PI Scenario 1, which was dominated by a contextual favorable global institutional environment and fast regulatory frameworks that allow for a quick development and adoption of new technologies. In this context, the port becomes open internally by 2030, which means that global alliances have fully integrated their vertical supply chains, while the terminals connect horizontally within the port. This "Physical Intranet" at the entire port community level scales up during the next 10 years, eventually reaching nearly all ports at the regional level. For the case of the Port of Rotterdam, this would mean including neighboring ports within the Hamburg-Le Havre range.

PI Scenario 4
On the contrary, the flattest or slowest evolution path was given by PI Scenario 4, which involved a challenging global setting of high protectionism between major power blocks and slow regulatory frameworks lagging behind market developments. In this context, the level of connectivity remains at the shipping line level, where alliances have vertically fully integrated their own dedicated terminals and supply chains by 2040. This could be seen as a form of "Physical Intranet" at the firm level. Yet, dedicated terminals remain unconnected within the port.

PI Scenarios 2 & 3
PI Scenarios 2 and 3 lied in between the other two. In 2030, "Physical Intranets" at the firm level are reached, which involve a complete vertical integration of supply chains within maritime alliances. During the next 10 years, dedicated terminals are slowly becoming more open to connect horizontally with other competing nodes within the port. This development is slightly faster in PI Scenario 2 than in PI Scenario 3, yet the "Physical Intranet" at the port community level has not fully been unlocked in any of these two future hypothetical futures.

Conclusions from the results
The PI Scenarios presented above ultimately try to round up the answer to the main Research Question proposed in this thesis. Moreover, from the results outline above, several conclusions could be drawn:

- All scenarios confirmed that the "Governance Dimension" is lagging behind in terms of development. By adopting the minimization rule proposed in Chapter 4, this layer seems to be the most critical out of the three proposed PI dimensions.
- From the PI Scenarios 2 and 3, it seems that panellists, on average, penalized more an environment of high protectionism (Scenario 3) than a future with regulatory frameworks lagging behind market developments (Scenario 2).
- Under the most optimistic scenario in terms of global institutional integration and regulatory frameworks (PI Scenario 1), the "Physical Internet" in ports as nodes of freight transport systems is achieved at the regional (European) level at most.

Recommendations for maritime ports
Based on the results of the four PI scenarios, recommendations were given to maritime ports in general, yet particularized for the Port Authority of Rotterdam, as the problem owner of this research.

- Maximize the slowest evolving of the three dimensions. Assuming that maximizing the level of port connectivity from the PI Port framework is desired, a high focus should be put on the "Governance Dimension", given the scenarios considered. As particular measures, the Port Authority could firstly play an active advisory role by evaluating and monitoring the implementation of the Rotterdam Rules in the Netherlands and neighboring countries within Europe. Secondly, regarding the CBER, the Port Authority could either promote its extension in 2020, or bring in together other stakeholders (i.e. port authorities or shipping line representatives) to discuss a more flexible version of the current CBER, while still in compliance with Article 101 of the TFEU.
- Avoid leaving the other PI dimensions overlooked. As a forerunner regarding the "Operational Dimension" and the "Digital Dimension", the Port Authority could play an advisory role with other port authorities and stakeholders so that the scaling up of the Physical Internet beyond port domains to a regional level can become a reality in the future.

These recommendations are still compatible with the current goal of the Port Authority of Rotterdam, which is to "enhance the competitive position of the port as a transport hub, in terms of volume and quality". Ports can attract more cargo while increasing their levels of connectivity within and beyond their domains.

6
Reflection on the thesis

The last chapter reflects on the entire approach taken for this thesis, as well as the major findings that have been identified throughout the research. Section 6.1 elaborates on the techniques used in different stages of the entire research, while Section 6.2 reflects on the outcomes identified throughout the thesis. Lastly, recommendations for further research are given in Section 6.3.

6.1. Reflection on the methodology

Chapter 2 proposed an approach that combined several techniques which together would produce a final outcome and answer the main research question. This section reflects on the methodology used throughout the entire thesis.

6.1.1. Literature review

Both Chapter 1 and Chapter 3 provided different sources of literature. This section reflects on the body of literature on the PI and maritime ports mainly and their shortcomings, leaving the context on scenario development for Section 6.1.3.

PI literature

A total of 41 publications were selected, reviewed and categorized. When comparing to other papers which conducted systematic literature reviews of the PI, many of the missing publications were not available in any of the search engines used in this project. Yet, the most cited papers in the field of PI are included in this project, from which many of the studies simply build upon. Therefore, it is considered here that the body of reviewed literature on the PI has been suffient.

The approach to derive the main PI characteristics as *means to an end* through a counting technique initially drew a picture with four terms. From this rigid approach, the four were then reformulated to three distinct characteristics, mainly to avoid misunderstandings for the interviews and the future Delphi. This pragmatic intermediate step did not follow a rigorous procedure rather than logic reasoning. A systematic literature review, a step wise approach to identify, assess and report findings on literature, could have provided more robust and clear characteristics. However, due to the young stage of the PI, and considering the lack of consensus on the topic, any approach taken could have given a different, yet valid or at least arguable, idea of the Physical Internet.

Port literature

The body of literature in the field of maritime ports is much larger than the young concept of the PI, and it encompasses many different levels of abstractions. The reviewed literature, from Chapter 1, focused on the role and especially the development of ports to position the research context mainly.

Reviewing the entire literature on the role and development of ports was considered to not be part of the scope of this thesis. The research context conducted from Chapter 1 was assumed to provide enough body of publications. Along with additional papers, reports and articles from Chapter 3, the different evolution levels of port connectivity could be determined. Nevertheless, the number of selected publications might still have been relatively limited. Moreover, no categorization was made related to the methodologies of the reviewed papers, as it was done with the PI. For these reasons, the author of this thesis acknowledges that relevant contributions in port literature might have been overlooked. Again, a systematic literature review approach could have allowed to select a number of publications proportional to the size of this thesis in a more rigorous way, while ensuring that their contributions are relevant to the scope herein presented.

6.1.2. Interviews

The selected experts for the interviews regarding the PI characteristics met the required criteria outlined in Chapter 2. Reaching up to 8 to 12 interviews could have given more breadth of opinions. Nevertheless, the chosen candidates spoke on behalf of different research communities both from the US and Europe related to the PI, and for that reason their opinions were considered to be sufficiently comprehensive. Moreover, preparing and conducting interviews is a time-consuming endeavour, and including more sessions would have delayed the work without adding additional insights apart from those already given by the previous interviews.

Because of the qualitative nature of the topic, there was no rigid structure in the format of the interviews conducted with experts. This avoided excessive bias from the interviewers, which could have unintentionally stirred the discussion into a particular direction. Experts had the freedom to give their feedback on the findings from the literature review and to provide their idea of what they considered to be the main PI characteristics. As a major drawback, the timing of the interviews was not strictly controlled, and little time was left at the end of each session to discuss the contextual factors needed for the next stages of the thesis. Moreover, with interviews that lasted between 1 hour and 2 hours, fatigue was visible among some of the experts towards the end of the sessions.

The insights from the interviews helped envision a more general foundation of the Physical Internet, complementing the findings from the previous literature review. The PI characteristics extracted from the experts were accounted equally, and they were mapped into what the author, together with MSc candidate Jeff Voster, considered as three distinct dimensions through several brainstorming sessions. This pragmatic approach allowed to construct a logical narrative of the Physical Internet, which could be used by both students in next stages of research. Yet, the process lacked a more systematic approach which could have given a better rounded vision of the PI.

6.1.3. Scenario development

The research context on scenario development from Section 1.3.3 was conducted to position the thesis, from which the research gap, the research goal and the (sub) research questions were formulated. In line with the purpose of the thesis, explorative scenarios were considered as suitable. Participatory methods, such as workshops or Delphi sessions, are usually considered for high levels of uncertainty, where relevant information cannot be easily quantified, which was the case of these explorative scenarios. Instead, as explained in Chapter 2, the guidelines from Enserink et al. (2010) were used instead to develop the contextual scenarios, and in turn these would be used as input for a Delphi study to elaborate the so-called PI scenarios. Several things need to be highlighted with respect to the methodology used to elaborate the contextual scenarios.

Contextual factors were identified from literature study (papers or reports), the already mentioned interviews and brainstorming sessions. As already said, the input from the experts was limited provided that little time was given for this purpose at the end of the interviews. The major source thus came from literature and the brainstorming sessions.

The clustering of contextual factors into driving forces was done through logic reasoning, based on the sources of information mentioned above. The PESTEL framework, a common and more rigorous way to identify trends and megatrends for studies of the future, was not used strictly in this thesis. The allocation condition to a particular dimension of the PESTEL was in turn relaxed to allow for flexibility in the identification of contextual factors and their corresponding driving forces. A missing step in the thesis was to ensure orthogonality of the clustered driving forces. Moreover, it is important to point out that the number of scenarios to be generated was aimed from the beginning at 8 or less, which translated, based on the chosen methodology, to no more than 3 driving forces. Because of these, the risk of overlapping was then perceived by inter-dependencies between the clustered driving forces. To identify the most relevant driving forces, the author of this thesis gave a strict definition to the "system" so that they could be assessed, based on impact and uncertainty, in a systematic way.

The narrative of each contextual or explorative scenario was built based on a combination of the directions that each selected driving force would take individually. The fact that these would be used as input for a further Delphi study biased the scenario logic. The direction of the driving forces were considered homogeneously per scenario. This means that geographical, societal or political factors, which could translate to the same driving force evolving in different directions or paces (i.e. between two countries) were not taken into account. Other factors were kept as constant for all the contextual scenarios to narrow down the spread of options (i.e. EU remaining contended) at the cost of potentially limiting the imagination of participants.

6.1.4. Delphi

Fatigue and non-response in the Delphi were significant concerns for the author of the thesis. Considering that the academic community of the young concept of the PI is relatively limited, the approach used within the different steps of the Delphi were adapted to mitigate these potential issues.

Firstly, the condition of "knowledgeable" expert was relaxed, assuming that an expert in the PI would be knowledgeable enough in maritime ports. This way, the number of potential participants would open room for more opinions. In this sense, a "port knowledge" criteria was not checked among the potential candidates. Likewise, it was decided from the beginning to conduct two Delphi rounds, so that the non response effect would be reduced.

To draft and send the questionnaire to the panellists, an online platform was considered. This was a simple way to collect anonymous responses from panellists located geographically apart. Albeit being an user-friendly tool, it is not fully tailored for Delphi studies. In this sense, the author had to design a survey that tried to capture all the essence of the framework and the contextual scenarios, to avoid fatigue among the participants, while mitigating some of the technical limitations of the platform. The wording presented from the framework had to be carefully checked so that all experts could understand what each dimension entailed completely. A potential drawback was that questions could arise half way throughout the survey. To define and clarify the topic as much as possible, a PDF summary was attached in the first round.

While the framework of the PI Port was categorical, which translated to a five-point scale in the survey, the author used the results from the Delphi to assign ratios to the different levels and that way give more room for interpretation of the results. While accepting that experts might have not though of an intermediate level (i.e. between Level 1 and Level 2) when making a particular selection, the use of descriptive statistics, such as the mean and standard deviation, allowed to further interpret general tendencies with respect to the three PI dimensions and the used driving forces. Yet, the collective responses analyzed and presented to experts at the beginning of Round 2 were limited to the percentage of votes assigned to each level. While this might seem overly simplistic, presenting them with the mean and standard deviation could have also given a misleading view of the results, and eventually lead to a common threat in Delphi surveys, which is the convergence of opinions towards more than one category.

Lastly, the Delphi was also used as an opportunity to get feedback from the panellists about different stages of this thesis. These open responses helped reflect on the different intermediate outcomes of the research, from the PI Port framework and contextual scenarios to the Delphi itself. However, for anonymity reasons, the author did not ask panellists about their personal information within any of the rounds. This included not asking them the sector (academia, industry, policy, etc.) they came from. Knowing whether a particular answer came from someone from a particular sector could have given extra insights. Instead, the responses were regarded as equally important.

6.2. Reflection on the outcomes

The approach taken throughout the thesis provided not only a final outcome, but also insights along the way which can enrich the debate around the Physical Internet in the context of maritime ports. This section reflects on the PI Port framework, the generated contextual scenarios, and the final PI scenarios from the Delphi study.

6.2.1. PI Port framework

As already said in Section 6.1.1 and Section 6.1.2, the insights from literature and the interviews helped envision a general idea of the Physical Internet. The PI characteristics extracted from the experts were accounted equally, and they were mapped into what the author, together with MSc candidate Jeff Voster, considered as three distinct dimensions through several brainstorming sessions. This pragmatic approach allowed to construct a logical narrative of the Physical Internet in the form of the PI Port framework, which could be used by both students in next stages of research. Several things need to be outlined about the resulting PI Port framework.

First of all, the framework focuses on a particular port and its hinterland. Yet it misses insights on its sea connections. As mentioned in Section 1.3.2, two port nodes are needed at least in sea freight, one acting as the sending end, and the other acting as the receiving end. Including this element could have depicted a different evolutionary model. Moreover, the framework assumes to be generic and applicable to any single maritime port. Nevertheless, when looking into the "Current State", some ports lend themselves better to the framework, such as global hubs like the Port of Rotterdam, than others. Besides the mismatch in the first level, there could be ports, or all ports in general, evolving in different ordering of the cells, as identified by some of the panellists during the Delphi study. This would confirm the notion that "all ports are, to some extent, unique" (Beresford et al., 2004). In line with the previous, the evolution of the three dimensions could only be assessed in terms of the pace, as a function of contextual scenarios, rather than in terms of content of the cells. Other developments which are aligned with the philosophy of the PI could be proposed as well. Moreover, the potentially limited literature review on maritime ports could have translated to a framework with missing elements and levels of abstraction in the topic. For instance, as identified by some experts, the relationship between ports and cities was not included in the framework.

From the PI perspective, the proposed dimensions could have described an incomplete image of the novel concept. This is however in line with the current lack of consensus about the PI characteristics. The diverging trends in the definitions and research across academia suggest the need for a holistic unification of PI from a conceptual point of view, which would be a time-consuming endeavour for this master thesis.

Moreover, the framework deals with the influence of PI dimensions over the evolution of "port connectivity". Both the quantitative and qualitative results suggest an inter-dependency of the dimensions, with the "Governance Dimension" playing a larger role than the other two, followed by the "Operational Dimension" and the "Digital Dimension" respectively. Moreover, with these inter-dependencies, a synergetic effect is achieved, suggesting that the PI itself is more than the mere sum of the three PI dimensions independently.

Lastly, it is important to note that the PI characteristics are highly reliant on a myriad of technological changes and innovations. These transitions result from a development path from niches to developed regimes. The bottom-up evolutionary approach tried to acknowledge this, yet without a consistent theoretical framework that could show a more robust transition of those developments.

6.2.2. Contextual scenarios

As it was already mentioned, strong inter-dependencies were spotted between some of the driving forces, which can affect the way each of them develop. For instance, technological developments can have an impact in any dimension, be that environmental, economic, societal or political, and thus in most of the other driving forces. Likewise, several studies suggest that increasing population might also be linked to climate change. Moreover, the "Melting of the Artic Pole", a contextual factor from the driving force "Flow Patterns", might be highly dependant on the "rise of temperatures", a contextual factor from "Climate change". "Flow patterns" in general might also be sensitive to changes in "trade agreements", yet they were considered as separate.

Moreover, the number of contextual scenarios could be seen as insufficient to envision all the possible future trends that affect, for the case of this research, the evolution of the Physical Internet. Yet the chosen size set goes in hand with the recommendations and outcomes of other transport scenario studies. The author considered the chosen combination to be constrained enough while giving sufficient spread in the scenario logic and room for imagination to the experts without excessive overlapping. This hypothesis was in turn subject to feedback from the experts. Some addressed the complexity of the topic to encompass it in the four proposed contextual factors, while others remarked that the two driving forces where clearly inter-dependent, much more than what the author assumed. As can be seem, any logic reasoning could have given different, both arguable and valid, driving forces.

6.2.3. PI Scenarios

The contextual scenarios, together with the PI Port framework, were translated through a Delphi study to PI Scenarios. Therefore, any potential shortcoming in the two previous described above could have cascaded down to the outcomes from the PI scenarios.

First of all, it must be noted that the results of the Delphi are for a particular combination of driving forces that the author considered, through logic reasoning, as relevant. Other elements might have been overlooked, and could have drawn a different evolution path of the three PI dimensions. For that reason, the results presented should not be unequivocally conclusive. As already mentioned in Section 6.2.2, previous check rounds with panellists could have been used to derive the main contextual factors and resulting driving forces. This could have however excessively increased the length of the entire Delphi, and eventually increase the non-response rate, a big concern for the author from the beginning.

Moreover, some participants dropped out half way through the survey acknowledging that the entire topic (PI and maritime ports) was not truly their area of expertise. For this reason, a first check round to assess the suitability of potential candidates as both PI and port experts might have indeed been necessary. In fact, since the author could not ensure the suitability of panellists with respect to the field of ports, (as stated in Section 6.1.4 it was assumed that any expert knowledgeable in PI would be knowledgeable enough in ports), it was not possible to know if there were subjects, who realized half way through the round that they were not knowledgeable to complete the survey, that simply continued filling in the survey with the purpose to help the student increase the response rate. For this reason, an extra validating step of the responses from the panellists might have been necessary.

Lastly, to compute the level of port connectivity for each PI scenario, the author adopted a minimization rule. Using a different criteria (i.e. average of the three dimensions) could have given different results from those herein presented. Yet, the minimization rule was done in line with the logical step wise approach taken to construct the PI Port framework, from the "Current State" to "Level 4". Moreover, it allowed to see the evolution path of port connectivity from a conservative perspective, since it depicts the lowest possible evolutionary levels.

6.3. Recommendations for further research

The last section of the chapter offers recommendations for further research in the field. The resulting outcome of this work tried to make a relevant contribution to fill in the identified research gap:

Current literature does not provide insights into the way possible future developments of the Physical Internet can influence the evolution of maritime ports.

The research goal focused on generating scenarios that would show the evolution of maritime ports under the influence in the development of the Physical Internet, so that Port Authorities could consider such effect in their strategic policies and therefore adapt accordingly. The findings from this thesis focus not only on the final outcomes but also on the intermediate steps, opening room for insightful research that can further build upon the topic of the Physical Internet in the context of maritime ports. Considering the large room open for research within the topic of the PI, and based on the discussions from Section 6.1 and Section 6.2, the following are proposed for further research from the context of this thesis.

First of all, further research should conduct a systematic literature review on both the Physical Internet and the evolution of maritime ports. The findings can then be complemented through a participatory approach (i.e. workshops or interviews). This way, the chances to overlook important characteristics and levels of abstraction within both topics, especially with respect to maritime ports, might be lower.

Secondly, as it was already mentioned, the resulting framework lacked the use of a theoretical foundation that could allow to see how the different PI characteristics evolve over a wider range of socio-economic factors. This relates to a finding already pointed out by Treiblmaier et al. (2016), which stated that in the PI research, a "theoretical base is highly underdeveloped". For example, adapting the lenses provided by Geels (2002), used for technological transitions, to this research, could potentially build more theoretically grounded evolving PI dimensions, and thus generate a more robust framework from which PI scenarios could be outlined, while fostering further intellectual exchange in the topic between the academics [See Appendix I for a further explanation of the approach from Geels (2002)]. Other models could also be explored as well, such as the political economy framework by Feitelson and Salomon (2004) or the integrated framework of Markard and Truffer (2008).

Thirdly, an in line with the discussion from the end of Section 6.2.2, the contextual scenarios presented in this thesis might be limited compared to the wide range of possible hypothetical futures. Instead of the guidelines from Enserink et al. (2010), a participatory approach could have opened room for more valid contextual scenarios. Extra pre-rounds of the Delphi could have been used with the sole purpose to identify these contextual factors by the experts. Consensus would not be strictly necessary, since the intention here would be to give the panellists free room to identify future streams. Yet, provided that little convergence is recommended among experts to avoid non-logical or contradictory opinions, two rounds would then be needed. With the resulting explorative scenarios from this first Delphi study, a second two-round Delphi could then be used to generate the PI scenarios, as it has been done in this thesis. Adopting this approach instead would have nonetheless been a time-consuming endeavour, taking much longer than the requirements of a master thesis. Furthermore, more scenarios coming from experts, which are simply providing their opinion and educated guess, would not necessarily lead to a better quality than those that would come from the methodology adopted in this research. An alternative could be to use the same methodology for generating contextual scenarios, but replacing the approach for the Delphi. Since more contextual scenarios increases the length of the survey, and therefore the risk of fatigue among panellists, it is recommended to conduct in-person workshops for further research. This way, the experts in the field of PI, a limited community in comparison to other well-established fields, can participate in a more engaging session while avoiding the fatigue factor. SENSE workshops or the annual IPIC conference can be a good opportunity to conduct such sessions.

Lastly, it is recommended to quantify the impact of the evolution of the Physical Internet in maritime ports. Building upon the research goal presented in this thesis, estimating future cargo flows within the context of the PI for each scenario could further help Port Authorities design appropriate policies, strategies and related infrastructure. From here, identified potential threats and opportunities based on the different PI freight networks depicted per scenario, a roadmap of actions that ensure maritime ports succeeding in their strategic goals could be proposed.

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Appendices

A. Documentation attached to interviews

The paragraphs shown below depict the exact text presented, via a Word document, to the experts during the four interviews.

1. PI Characteristics:

As part of our MSc thesis, we needed to make a conceptualization of the Physical Internet and the way it can affect Port Systems. This is done based on (1) (systematic) literature review and (2) Experts Interviews. With (1) the main components are found, and these are used as input for validation in stage (2) with the experts.

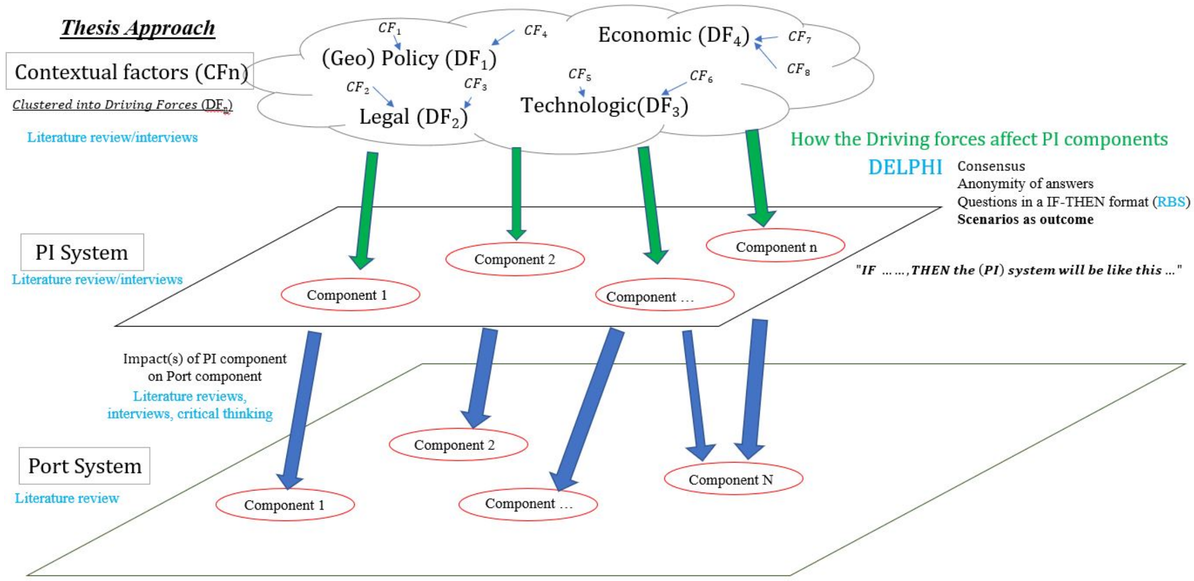
Findings from the literature review

A solid definition of PI is not fully clear when one dives into the literature, suggesting that the concept is still in its infancy. Seems that any approach taken can give lead to different, yet valid or at least arguable, definition to the PI an its components. Based on this, a pragmatic approach was taken. The components where considered as the "means to an end", with the later being an "improvement of the way physical objects are moved, deployed, realized supplied, designed and used". With the formal definition given by Montreuil, and quoted by several of the other publications, the components found were initially (1) Modularity, (2) Encapsulation, (3) Interfaces, and (4) Protocols (highest number of counts on the literature). While diving deeper on these 4 components, they were restructured into the following 3 final components:

- ***Modularity:*** *One of the core components of the Physical Internet. In our case, we take a broad definition, arguing that it does not just encompass the modular PI-containers, but also the encapsulation of all types of goods in these boxes. 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 boxes and stack these int composite 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 publish in real time their available capacity, 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". That is, they can share information, communicate and make decisions automatically which 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 such 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.*

With these 3 components we try to capture everything (or at least most of) what the PI entails as enablers of the vision. There are other elements which in some papers were considered as "components", such as legal frameworks or business models. We argued that these would be considered as "external factors". That is, these would affect the development of the Physical Internet[1].

The following image shows the heuristic approach taken. We need to validate the intermediate layer (PI components) as well as the external/contextual factors, which are clustered into driving forces (top layer).



[1] in a later stage of the Scenarios thesis, a Delphi is meant to be conducted regarding how the External Factors, clustered into driving forces, affect the development of the PI components, to be asked in a Rule-Base System format (i.e. If Driving Force 1 is High, AND Driving Force is 2 is High, AND Driving Force is High, THEN Modularity will be High/Medium/Low, Collaboration will be High/Medium/Low, and Interconnectivity will be High/Medium/Low.

2. Contextual Factors:
The idea here is to look into external or contextual Factors which affect what we consider as the System, which in this case is the Physical Internet itself. In other words, we want to look into the Contextual Factors that affect the development of our PI Components. We have researched/brainstormed and have come up with the following list. This is a first draft, and the idea is to discuss them with you:

Contextual Factors	Explanation
Population Growth	Worldwide population growth
Economic Growth	Countries grow economically, which can lead to more traffic
Urbanization	Increase of urban densities
Belt and Road Initiative	New project developed by China
Rise of temperatures	Rise of temperatures as a result of global warming
Automation	Automated equipment, algorithms and other elements that replace human beings
Mass individualization	People demand more customized products
Migration flows	i.e. refugee crisis, search for better opportunities which lead to migration flows
Rise of 3PL and 4PL	Different layers of outsourcing of logistics
Increase of vessel size	Ships get bigger and bigger
Global monopolistic operators	Big players controlling everything (Maersk, ECT terminals, Amazon,. . .)
Competition between companies	From individualistic models to more cooperative
Awareness of environment	From a societal perspective, which translates to greener policies
New technologies	Innovations from all perspectivese (blockchain, IoT, Hyperloop,...)
Port Centric Logistics	Port become global hubs of transport networks (everything via ports)
Truck usage policies	Tightening policies in the EU against trucks
Depletion of natural resources	Resources such as oil or other natural resources
Political situation in Europe	United or divided Europe
Trade wars	Rise of tariffs between, for example, China and the USA
Circular economy	Shift to the 3Rs (recycling, reduce, reuse) and upcycling
Service economy	No production, only imports
3D printing	Localized production of goods
Lobbying pro curent standard TEUs	Established companies with high assets in TEUs lobby against the new PI-containers
Environmental regulations	Policies to reduce or mitigate the effects of climate change

As can be seen, this is still in a draft phase. In short, the Driving Forces (some of which have a direct effect on Ports, others on our 3 PI components, and others on both) we initially have in mind are the following:

- Trade patterns
- Environmental
- (Geo)political
- Technological
- Societal
- Business models
- Legal

B. Interview with experts

This Appendix shows a more detailed explanation of the four interviews conducted with the experts.

Interview 1: Dr. N. Szirbik and Dr. G. van der Heide

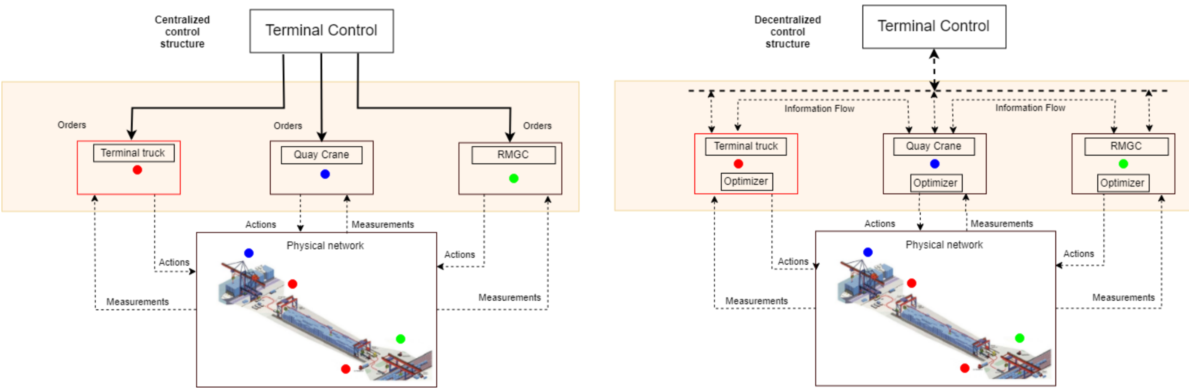
Dr. (Nick) Szirbik, from the University of Groningen (Netherlands), is an expert in complex systems modelling for operations and agent-oriented scheduling. He currently supervises master students in PI-oriented research regarding the communication structure between the different players in the PI-network. Dr. (Gerlach) van der Heide is a postdoctoral researcher also from the University of Groningen, and is currently involved in the new research "Towards virtual ports in a Physical Internet" from an Operations Research perspective. Since they met the expert criteria defined in Chapter 2, they were considered as suitable "experts" in the field of PI.

The interview, which was conduced in person and lasted for approximately 1 hour and 20 minutes, followed an unstructured format. This was done to avoid bias, allowing the interviewees to talk about their vision of the Physical Internet. As a first remark, the experts pointed out that the approach taken by the author in the systematic literature review was "perhaps too rigid", and could lead to an incomplete view of the Physical Internet. They then defined what they both considered to be the main "pillars" or foundation principles of the PI. The term "pillar" had the same definition of what this thesis considers as "characteristic" or component. Their view of the Physical Internet is founded on "the following components":

- **Modularity.** The definition of this pillar or component is similar to what was obtained from the literature review. They referred to the encapsulation of different goods into a set of standardized modular containers which can be easily handled and inter-locked on the different carriers and equipment adapted for the PI environment.
- **Openess.** "The most important pillar" according to the consulted experts. It refers to the accessibility or democratization of any type of stakeholder, from producers to carriers or consumers, to make use of the Physical Internet. Similar to what L. Tavasszy (2018) suggested, the access to the different markets are available to everyone in the PI. For instance, Small and Medium Enterprises (SMEs) can now more easily afford to access to markets which were before limited to the bigger players. As an example, a restaurant located in the Netherlands who wanted to purchase wine from a particular small vineyard located in the south of France, could now "log in" into a PI-based cloud and purchase the products directly from the producer, instead of relaying on big retailers. Regarding the transport, "you let the cloud do the rest".
- **Decentralization.** From an agent-based perspective, a decentralized structure removes the traditional central planner which gives guidelines to all the actors situated hierarchically bellow. A simple example could be the control structure of a traditional container terminal. The Control Center gives orders to transport components, such as the terminal trucks, Rail Gantry Mounted Cranes (RMGC) or Quay Cranes handling deep sea container vessels, about what their next moves should be. In a decentralized control structure, the transport components[2] would communicate with each other at a horizontal layer and perform their activities to reach

[2]In this context, "transport components" are given the meaning by Negenborn et al. (2010), which refer to the physical vehicles or equipment, automated or human-driven, which perform transport activities, such as terminal trucks, cranes, conveyor belts,etc.

their operational or short term goals (i.e. maximize throughput). Each component has a digital "agent" associated to it, which takes care of the communication and other protocols such as the routing throughout the terminal. These are aligned with the tactical, longer-term objectives of the Terminal Control Centre, which would limit its intervention on the actors of the lower layers to special cases, such as in the case of conflict between two components[3].



Example of a decentralized multi-layer control structure for a container terminal.

- **Automation.** According to the experts, this is also another fundamental pillar of the PI. The potential efficiency benefits can be truly exploited where all the actors in the supply chain have their communication, negotiation, scheduling, planning and any other operation done without the need for human intervention. Looking again to the example depicted above, the automation can be seen from two levels in the decentralized structure. First, transport components are represented by a digital agent which takes care of all the information sharing with the rest of the actors regarding, for instance, their status (position, velocity, acceleration, etc.). This can also be referred to as "digitization". Based on this information, the agent decides on the next move and the routing, for example the position of next container to pick up. Secondly, the handling and transport itself can be done through automated equipment. Instead of container trucks, Automated Guided Vehicles (AGVs) could be used.

Little time was left at the end to discuss the list of contextual factors that the author and MSc candidate Jeff Voster came up with, needed for Chapter 4. Instead of going through the entire list, the experts identified what they considered as relevant contextual factors for the development of the Physical Internet. These were "mass individualization", "cybersecurity" and "demand of SMEs for transport".

Interview 2: Prof. Dr. B. Montreuil

As leader of the Physical Internet Initiative, Prof. (Benoit) Montreuil is a world-renowned scientist who has pioneered the paradigm changing vision of the PI. He is Professor in the H. Milton Stewart School of Industrial and Systems Engineering at Georgia Tech (USA). He is also the Coca-Cola Material Handling & Distribution Chair. Because of his extensive advisory, entreprenurial and collaborative research experience with both industry and government within the field of PI, Prof. Montreuil was by no doubt a perfect fit as an "expert".

The interview, which was held via Skype®, lasted for approximately 1 hour. On a first stage, after a brief introduction of the participants, an unstructured format was also followed, allowing the interviewed expert to first give some feedback about his vision of the PI and the findings from the

[3] For more information about Multi-Agent control structures, see Sycara (1998), Negenborn et al. (2010) or Maestre et al. (2011).

literature review. According to him, the term *collaboration* can be seen as a "dangerous word", since in his view it refers to current practices that are already being done by the biggest players in maritime transport. Despite the economies of scale that (big) companies get through "horizontal and vertical integration", major drawbacks can be seen, according to Prof. Montreuil. Firstly, big partnerships and alliances take several years to formalize, because of the long administrative and operational it undergoes. By the time the alliance is formalized, the market has already changed. These long dealing process make (rigid) collaborative agreements tough to adapt to the dynamics of the market. Lastly, a scale problem is suggested by the expert in the sense that collaborative agreements are closed to a limited number of players, whereas the market is composed by thousands of them. He proposed instead to use the term "cooperation", which allows for the so-called "hyperconnected logistics system". By hyperconnected he meant that "actors and components are intensely interconnected on multiple layers". These layers of *interconnectivity* are "digital, physical, operational, business, legal and personal". Only the digital and, to some extend, the operational interconnectivity, which refers to the capability of actors to communicate and share information and make decisions, was considered by the author of this thesis, as pointed out by the expert. The main pillars, or "building blocks" as he names them, to enable the interconnectivity on those six layers are the following:

- **Certified Open Logistics Service Providers.** A set of entities which can provide logistics services in the PI environment.
- **Smart Data-Driven Analytics, Optimization & Simulation.** Exploiting the potential benefits of advanced simulation algorithms.
- **Open Logistics Decisional & Transactional Platforms.** This block refers to digital interfaces which allow for a smooth business interconnectivity, that is, fast and reliable transactions, payments of contracting.
- **Global Logistics Monitoring System.** A system which allow for the digital interconnectivity, that is, the traceability and sharing of information.
- **Certified Open Logistics Facilities and Ways.** This refers to open facilities, assets or hubs that can be shared and used indistinctly by all the π certified players. This has an overlapping definition to the term *collaboration* found from the systematic literature review.
- **Standard Logistics Protocols.** Rules to be observed and understandable by everyone. As an example, he referred to Incoterm rules for managing transport, but also to real-time contractual agreements between the players.
- **Containerized Logistics Equipment and Technology.** These were referred to as the handling interfaces already discussed during the systematic literature review. The handling and transport equipment of containers would not necessarily need to be automated according to the expert, contrary to the opinion of the previous experts.
- **Unified Set of Standard Modular Logistics Containers.** This block refers to the π containers themselves, which are meants to be "easy to handle, store, transport, smart and connected, and eco-friendly".

As with the previous interview, there was little time left to go over the list of contextual factors provided by the two students. After a quick scan, the expert identified "increase in vessel size", "3D printing" and "Internet of Things" as important external factors

Interview 3: Prof. Dr. L. Tavasszy

Professor in Freight and Logistics at the TU Delft (Netherlands), Prof. (Lóránt) Tavasszy is specialised in transport modelling and freight transport. He has pioneered the "synchromodality" concept, which is considered as one of the intermediate steps presented in the roadmap towards the Physical Internet in Europe for the year 2040 (ALICE, 2018). As a member of the scientific committee for the past editions of the International Physical Internet Conference (IPIC), he plays an active role in collaborative research of the PI, leading several brainstorming sessions and workshops as part of the SENSE project. For these reasons, he was also considered a valid "expert" of the PI.

The interview was conducted in person and lasted for almost 2 hours. Before digging into his idea of the PI, he mentioned that there is ´difficulty to reach a unified definition of the Physical Internet´. He referred to the fable of "the blind men and the elephant", where each of the experts tend to perceive the vision from one angle[4]. As pointed out by him, any definition "can be valid". His starting blocks were the following:

- **Modularity.** This takes a broad definition, namely the entire physical and operational interconnectivity. Goods are encapsulated in π containers, which are then handled via different vehicles and equipment throughout the entire transport chain.
- **Cooperation.** Also taking a broad definition from a business and digital perspective, Prof. Tavasszy deferred to a continuous system-wide exchange of information, and a "strong cooperation between logistics actors". He pointed out that strong and flexible regulations will need to be developed, such as the upcoming "Rotterdam Rules"[5], which would potentially allow for synchromodality.

Prof. Tavasszy considered these blocks as the enablers of the "hyperconnectivity" that Prof. Montreuil referred to. The former remarked the importance of brainstorming with knowledgeable academics and professionals in the field of PI as a way to reach consensus towards a unified definition as a whole. For this reason, the SENSE project, where Prof. Tavasszy participates, serves as a way to gather experts in Europe to try to reach consensus on the PI and the steps, also known as *´PI Generations´*, it needs to undergo to reach the overall vision.

According to him, the knowledge from all the experts have been clustered into different "areas of interest", and each broken down into different evolving or intermediate time steps until the goal of 2040 proposed by the European Commission. These evolving steps are presented for "one scenario only, and from a transport perspective".

Lastly, instead of going through the list of contextual factors, the expert pointed out his opinion regarding relevant driving forces that influence the development of the Physical Internet. He mentioned that "in order to have strong cooperation between logistics actors, a crucial prerequisite of the PI, regulatory frameworks will need to enable these new business models. These are needed, yet if you prove to companies that they can benefit from cooperative models, they will shift to them [...]. In that sense, unlock new regulatory frameworks and companies will join seeking the benefits." This general concept was further discussed in Chapter 4.

[4]see The blind men and the elephant (Wikipedia).
[5]See Rotterdam Rules.

Interview 4: A. Nettsträter

Researcher in the Fraunhofer Institute for Material Flow and Logistics (Germany), Andreas Nettsträter is an active member of the PI community. He has lead several workshops regarding the topic and is one of the scientific committee members of the next IPIC conference, which will be held in London in July of 2019. He is responsible for the agenda of the SENSE roadmap. Given this position, he is entitled to be an important PI "expert".

The interview was held via WebEx® and lasted for approximately 1 hour and 20 minutes. After an introduction of his role at Fraunhofer, he spoke about the progress made at the SENSE project. As already mentioned by Prof. Tavasszy, SENSE workshops are the main source of PI knowledge-building in Europe, where the amount of experts who participate "range from 20 to 60". According to the interviewed, after more than "18 months of debate with many of the PI experts located in Europe, the definition of the PI is still under discussion". For this reason, a pragmatic approach was taken by defining what they considered to be "areas of interest". Each of them, defined "from a transport perspective", evolve into different intermediate steps or PI Generations, from the current situation to the goal of 2040. The main "areas of interest" considered in Europe are the following:

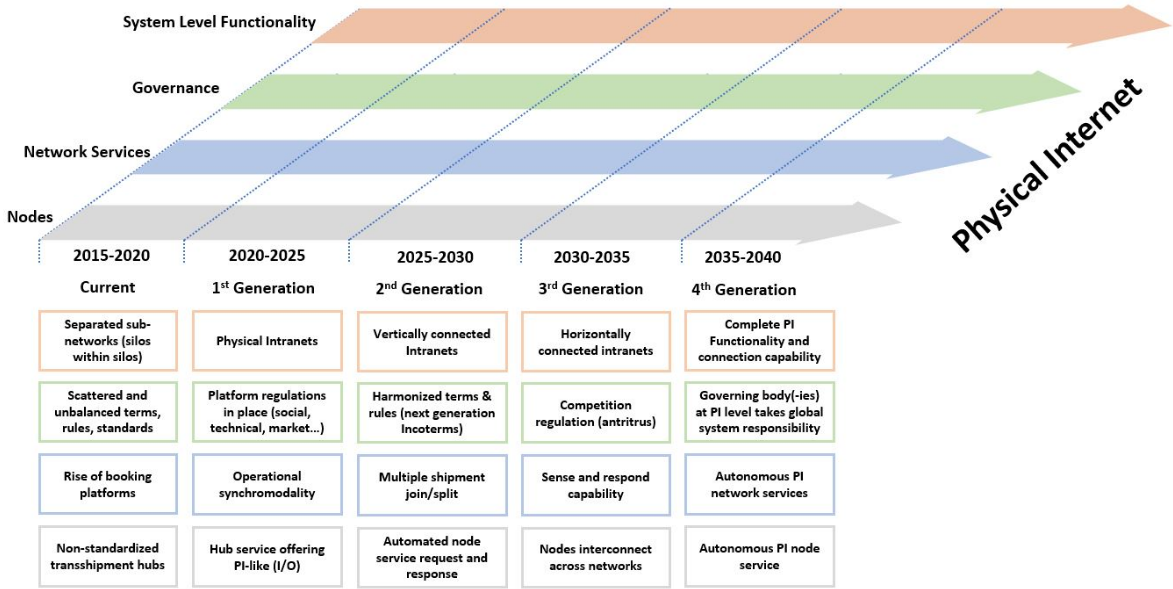
- **System Level Functionality.** This area relates to the way the different actors function in freight transport systems. In the current situation, not only are networks separated between companies, also the sub-networks, that is, the "networks inside the companies are separated". This stage is dominated by "alliances" - with the bottlenecks already pointed out by Prof. Montreuil-. The first step, or generation, is thus to create "Physical Intranets", or "connectivity of the networks at the company level". The next two sequential steps would be to reach "vertical and horizontal connectivity between companies". In the last generation, "complete connection and capability within and between all actors, where everyone has access to the Physical Internet", would be reached. Connectivity in this sense was used as a broad term, considering the interconnectivity from all layers (business, operational, physical, ...).
- **Governance.** This area refers to the set of rules needed for a cooperative, safe and reliable Physical Internet. In the current stage, dominated by the aforementioned separated sub-networks, "contractual terms rules and regulations are unbalanced and scattered". The generations relate to the implementation of terms or regulatory frameworks, first for existing "asset-sharing platforms"[6], and then scale them up to "harmonized terms for vertically integrated intermodal networks". In this regard, the expert referred to a new governance and tailored version of the current Incoterms©[7]. On a next step, asset-sharing and competition (antitrust) rules are implemented to allow for a complete "horizontal inter-network connectivity". At the last generation, a set of "governance bodies" are implemented for an "open global PI network".
- **Network services.** This area refers to the operational, digital and contractual elements that allow for fast, reliable and resilient logistics services in the Physical Internet. In the current state, a limited amount of "booking platforms" allow for different logistics services. "Operational synchromodality" would be considered as the first generation, where "services, routing or scheduling algorithms and processes would be implemented". The next step would enable what he referred to as a "multiple shipment join/split" process. With new capacity forecasting and assignment algorithms, along with new tracking and integration services, shipments could be in real time split and re-merged "on the route" and considering all the potential modes. The level of complexity of the protocols and digital interfaces would eventually evolve into "Fully autonomous PI network services and operations", considered as the last generation.

[6] An example of these small niches can be a company who provides on-demand open warehousing services, known as Flexe.

[7] For a brief introduction of the Incoterms, see Bergami et al. (2012).

- **Nodes.** From a network perspective, there will be different types of PI Nodes according to their size and scale, although the expert remarked there still a "need to create a taxonomy of PI Nodes". In the current stage, dedicated, non-standardized transshipment hubs are the norm in freight transport systems. In the first generation, once they meet IT, infrastructural and other technical requirements, "registered PI Nodes publish current capacity and storage capacities which become openly accessible by third parties". This openness evolves vertically so that different nodes in the same current supply chain can be interconnected. Following this generation, known as the "interconnected network of nodes", the next generation relates to the interconnection of different networks, thus allowing for transparency and openness both vertically and horizontally of supply chains. At a final stage, "fully autonomous operating network of networks with storage, automated handling and transshipment" would be in place.

The figure below summarizes the approach taken by the experts in the SENSE workshops (which include both the interviewed experts as well as Prof. Tavasszy):



Resulting main areas of interest of the PI and their Generations (ALICE.c, 2019).

As can be seen, these areas are defined on different levels of abstraction, yet all with a similar approach. That is, the evolution of the Physical Internet takes a bottom-up path, from the firm level to the global transportation network level. According to the expert, the first area refers to "what the system does", while the latest three to "what it takes" for the fulfilment of the Physical Internet. In this regard, albeit considering different dimensions, the latest three would be considered as their "building blocks".

A remarkable insight from this last interview was that the π-containers, a crucial element of *modularity*, are not considered to be a main building block of the Physical Internet. This is because "there is no need to put everything in boxes". As an example, "bulk, from dry to liquid, is a important segment in the cargo flows which will not need to be encapsulated in modular containers". Yet, these can still be moved and handled in the Physical Internet.

Lastly, the expert provided the students with documentation he had been involved in regarding trends and megatrends in logistics for the generation of future scenarios [see nextnet.a (2017) and nextnet.b (2017)]. This could serve as further input of the expert regarding all the contextual factors that the students had been initially working on [see Appendix A].

C. Digital Maturity Model

The PI Port framework proposed in Chapter 3 shows the evolution of a port towards a hyperconnected hub. This bottom-up evolutionary approach is similar to the so-called Digital Maturity Model proposed by the Port of Rotterdam, which the author used as source and adapted it for the "Digital Dimension". Divided into four "maturity levels", the white paper tries to envision how ports can evolve in steps to "keep up with digital developments" around them.

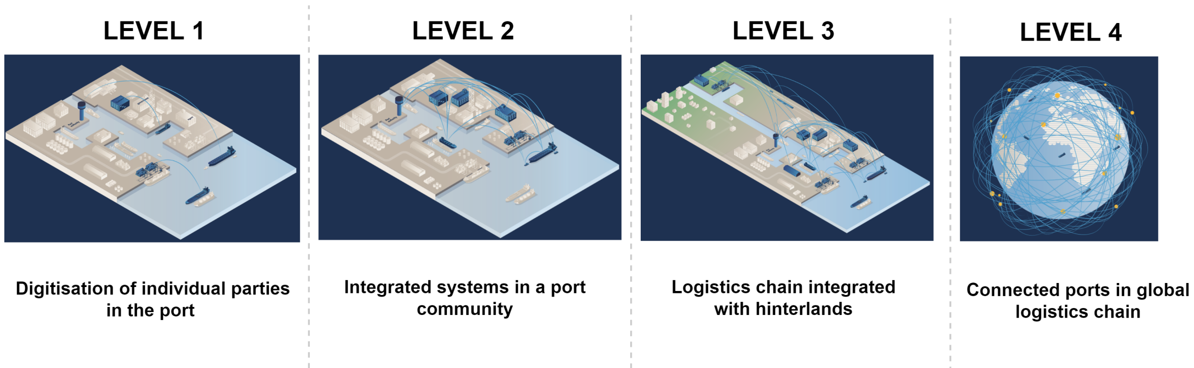
Maturity level 1 covers the digitization of individual parties within the port, which translates to more efficiency of their processes. An example is the so-called Port Management System (PMS) which, among other benefits, supports administrative and financial processing of port calls

In Level 2, the previous heralds the digital exchange of information within the port community, through the so-called Port Community System (PCS). Through PortBase for the case of Dutch ports, businesses can exchange mandatory notifications to authorities (B2G) or with other companies (BSB), such as the Estimated Time of Arrival (ETA).

Level 3 scales up by including the hinterland of the port community. Information from the PCS is also shared with players such as inland terminals, road carriers, etc. This translated a real-time insight into cargo and ship visits, allowing for a better and more efficient planning in the hinterland.

In the last maturity level (Level 4), communication of port communities and their hinterland is expanded to other ports around the world. This would mean an integrated door-to-door digital logistics chain created on a global scale, with an optimized use of different transport modes.

As can be seen, the Digital Maturity Model show how ports can evolve step by step towards what the white paper considers as "smart ports", with the focus on data sharing. With little transparency in current sea freight, the Port of Rotterdam acknowledged in this report the need for trust among competitive ports, which goes in line with the cooperative philosophy of the Physical Internet studied in this thesis.



D. Resulting contextual factors

ID	**Contextual Factor**	**Source**	Included
1	Population growth	Brainstorming; DHL (2012); nextnet.a (2017); WEF (2016); (PoR.c, 2018)	Yes
2	Economic growth	Brainstorming; DHL (2012); nextnet.a (2017)	Yes
3	Urbanization	Brainstorming; DHL (2012)	Yes
4	Pollution	Brainstorming; DHL (2012); nextnet.a (2017)	Yes
5	Automation	Brainstorming; DHL (2012); nextnet.a (2017); Interview 1 pwc (2016); WEF (2016);	Not considered
6	Future environmental regulations	Brainstorming	Yes
7	Mass individualization	Brainstorming; nextnet.a (2017); L. Tavasszy (2018); Interview 1; DHL (2012)	Yes
8	Migration flows	Brainstorming; nextnet.a (2017)	Yes
9	Rise of 3PL and 4PL	Brainstorming	Not considered
10	Hyperloop	Brainstorming; L. Tavasszy (2018)	Yes
11	Increase of vessel size	Brainstorming; T. Notteboom and Rodrigue (2009); Interview 2	Yes
12	Global monopolistic operators	Brainstorming; nextnet.a (2017); Heaver et al. (2001)	Yes
13	Cooperative models	Brainstorming; L. Tavasszy (2018); WEF (2016); PoR.c (2018)	Yes
14	Port Centric Logistics	Brainstorming	not considered
15	Melting of Artic pole	Smith and Stephenson (2013)	Yes
16	Belt Road Initiative	Brainstorming; (PoR.c, 2018)	Yes
17	Truck usage policies	Brainstorming	Not considered
18	Depletion of natural resources	Brainstorming; nextnet.a (2017)	Not considered
19	Political union in Europe	Brainstorming; WEF (2016)	Yes
20	Trade agreements	nextnet.a (2017); L. Tavasszy (2018)	Yes
21	Circular economy	Brainstorming; WEF (2016)	Yes
22	3D printing	Brainstorming; Interview 2; nextnet.a (2017) WEF (2016)	Yes
23	Innovative business models	Brainstorming; WEF (2016)	Yes
24	Internet of Things	Brainstorming; Interview 2; L. Tavasszy (2018); DHL (2012); WEF (2016); PoR.c (2018)	Yes Yes
25	Big Data	Brainstorming; nextnet.a (2017); L. Tavasszy (2018); DHL (2012); PoR.c (2018)	Yes
26	Artificial intelligence	Brainstorming; nextnet.a (2017); DHL (2012)	Yes
27	Blockchain	Brainstorming; nextnet.a (2017); L. Tavasszy (2018)	Yes
28	Drones	Brainstorming; nextnet.a (2017); ; L. Tavasszy (2018); WEF (2016)	Yes
29	Lobbying pro current standard TEUs	Brainstorming	Not considered
30	Cybersecurity	Interview 1; nextnet.b (2017)	Yes
31	Demand of SMEs for transport	Interview 1	Not considered
32	Import tariffs and quotas	nextnet.a (2017)	Yes
33	Different tax environments	nextnet.a (2017)	Yes
34	National subsidies	nextnet.a (2017)	Yes
35	Nearshoring	PoR.c (2018)	Yes
36	Antitrust policies	L. Tavasszy (2018)	Yes
37	Labor protection	Brainstorming	Yes
38	Individualistic models;	Brainstorming	Yes
39	Rise of temperatures	Brainstorming; nextnet.a (2017)	Yes

E. Scenario logic

The scenarios outlined to the experts in the online survey, which result from the different combinations between the two selected Driving Forces (´global integration´and ´regulatory frameworks), are presented in the next four tables:

Scenario 1
It is 2040 and the globalization process have spurred the rise of democracies in developing countries. With rising incomes, domestic consumption has increased in Eastern countries, South America and Africa.. Intercontinental trade has increased at a similar pace than in the past 20 to 30 years, and more intra-regional supply chain demands are the new reality, a process known as 'glocalization'. *Moreover, regulatory frameworks have somewhat adapted quickly to the political, economic and societal settings in the past 20 years in the EU and other major power blocks. This has lead to a significant technological development and adoption, and has opened room for new cooperative platforms from which companies can further profit. In the maritime sector, where collaboration already existed through powerful alliances and consortias, have been interested in more flexible forms of cooperation for the past 20 years.*

Scenario 2
It is 2040 and the globalization process have spurred the rise of democracies in developing countries. With rising incomes, domestic consumption has increased in Eastern countries, South America and Africa. Intercontinental trade has increased at a similar pace than in the past 20 to 30 years, and more intra-regional supply chain demands are the new reality, a process known as 'glocalization'. *Nevertheless, regulatory frameworks have generally thwarted the adoption of technological developments. With regulations lagging behind market development, the digital transformation has been generally limited to the biggest companies, the only segment that can afford new technological developments and thus their benefits. In the maritime sector, global alliances have continued integrating their own supply chains.*

Scenario 3
It is 2040 and the world is dominated by high protectionism between the major power blocks. The enclosed political environment of the world leads to a EU policy of protecting domestic industries against foreign competition. Despite rising nationalistic movements in few of the member countries, which try to follow the steps of the UK, the European Union has remained contended throughout the past 2020, yet challenged by these internal disputes. Also, global trade has still grown world-wide within the past years, although at a lower pace than the estimates made during the 2010s. *On the other hand, regulatory frameworks have slowly adapted to the political, economic and societal settings in the past 20 years in the EU and other major power blocks. This has lead to a moderate technological development and adoption, opening room for cooperative-based niches from which companies can further profit. In the maritime sector, global alliances have been slightly affected by rising protectionism.*

Scenario 4

It is 2040 and the world is dominated by high protectionism between the major power blocks. The enclosed political environment of the world leads to a EU policy of protecting domestic industries against foreign competition. Despite rising nationalistic movements in few of the member countries, which try to follow the steps of the UK, the European Union has remained contended throughout the past 20 years, yet challenged by these internal disputes. Also, global trade has still grown world-wide within the past years, although at a lower pace than the estimates made during the 2010s.
In this context, regional regulatory frameworks have lagged behind market developments, and therefore technological adoptions have been limited to the biggest players. Global maritime alliances have been able to use new technological developments to adapt to the new circumstances.

F. Documentation attached to Delphi survey

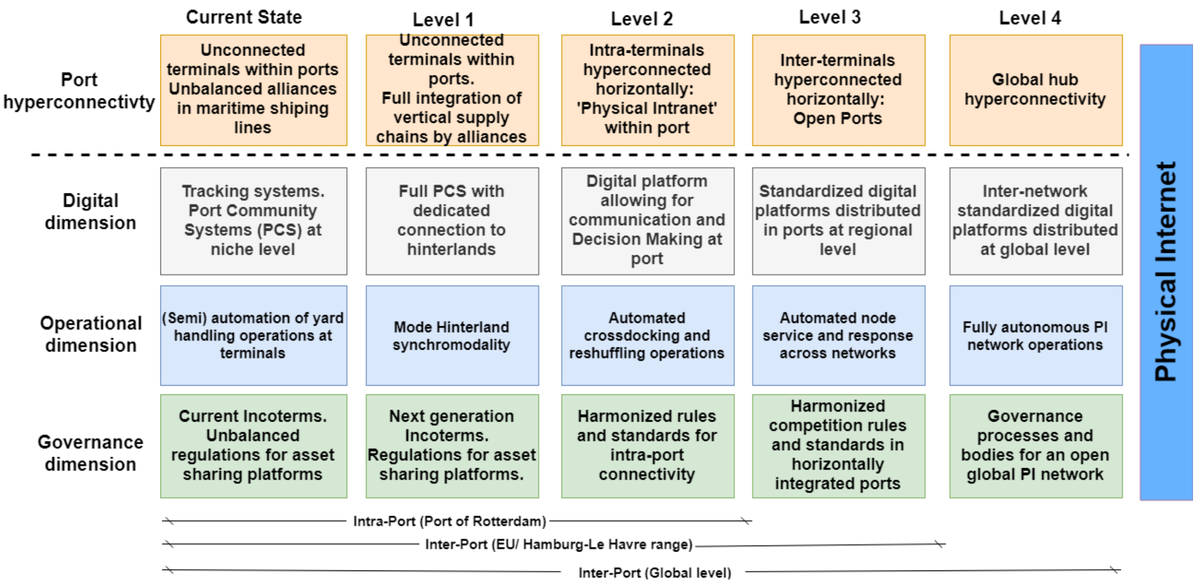
Round 1
For the first round of the Delphi survey, an e-mail was sent to the experts with the link to the questionnaire, and a 2-page PDF document briefly summarizing the entire thesis. The document contained the following:

Thesis summary:

The Physical Internet is a novel concept that could change the way logistics are conceived nowadays, and to the best of the author's knowledge, its impact on maritime pots has remained unexplored. This research aims to provide insights into contextual scenarios in which the PI could evolve, and the impact of these in the evolution of maritime ports, and is divided into two distinct parts.

PI Conceptualization:

In the first part, a conceptualization of the Physical Internet has been carried out through a systematic literature review, to derive its main characteristics. Three overall PI dimensions (digital, operational and governance) were defined, which tried to capture all the knowledge built around the 41 papers and the 4 interviews conducted with experts in the field, and were then scoped down to maritime ports. Using the Port of Rotterdam (PoR) as a reference, a bottom-up approach was proposed which shows how the port would evolve towards a global hyperconnected hub, or 'PI Port', as a function of the three PI dimensions. This is shown in the Figure below:



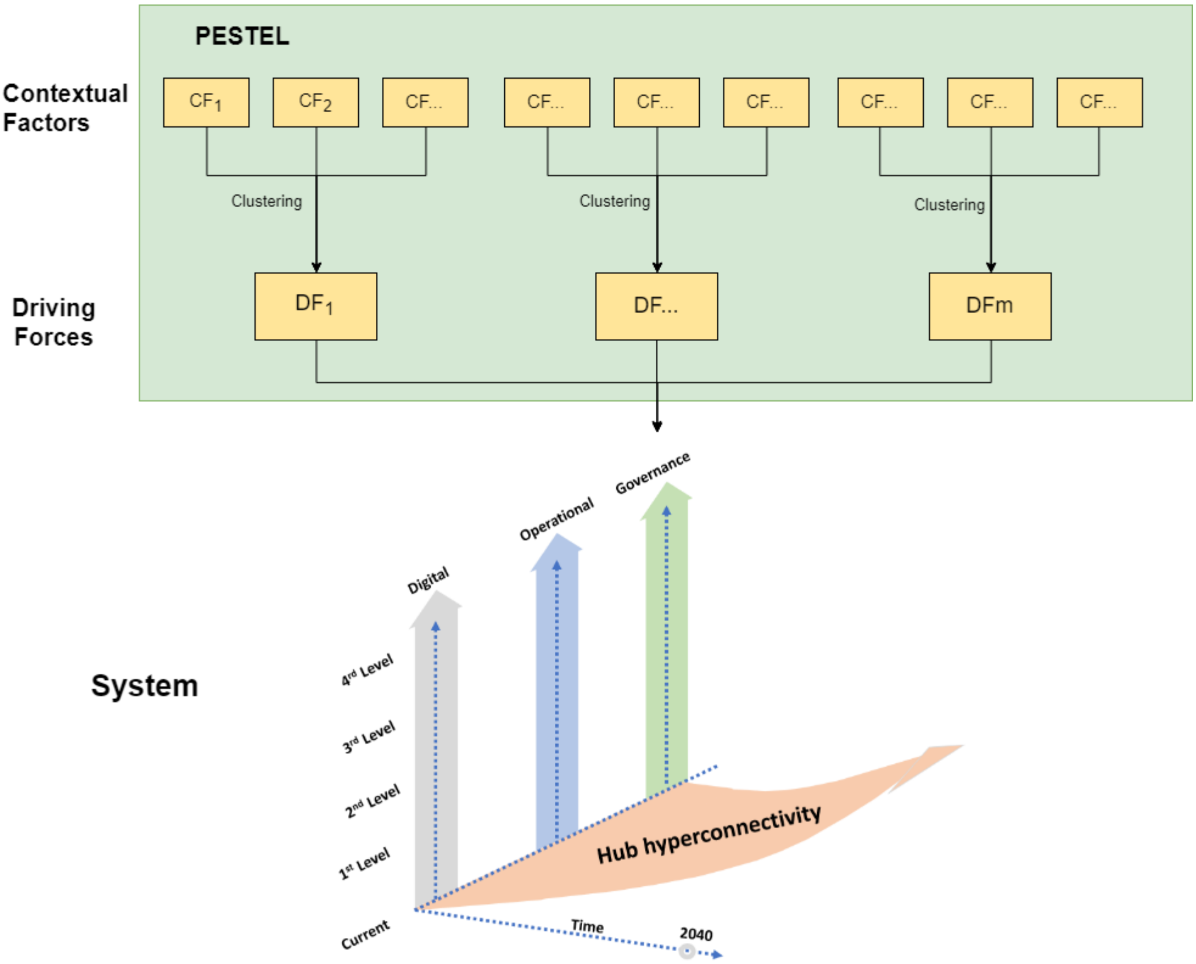
The evolution towards a PI Port (orange cells based on three PI dimensions.

In the current state, the author argued that ports nowadays are not connected internally, with each terminal dedicated to its own company or maritime alliance. Therefore, a current state of 'silos within silos' could be considered. In the next stage (Level 1), complete vertical integration of supply chains by the alliances could be considered, yet with terminals still unconnected horizontally inside the port.

A fully developed Port Community System (digital dimension) could allow for vertical communication between different parties. On a B2B bases on the one hand, with respect to general quests (ETA/ATA/ETD) and on a B2G basis for administrative purposes (Customs, IMOFAL,...). In level 2, same cargo segment terminals are open and horizontally interconnected within the port, and therefore 'Physical Intranet' of the entire port community is achieved. In level 3, hyperconnectivity of the terminals go beyond the boundaries of the port itself, reaching other competing ports in the same region (Hamburg-Le Havre range). In the last level, the previous hyperconnectivity is generalized to global networks, where border protocols connect regional areas (i.e. PoR and Port of Singapore). As can be seen, each level of port hyperconnectivity evolves as a function of the 3 PI dimensions.

Scenario Development:

In the second part of the thesis, contextual factors were clustered into driving forces. Then, the most relevant based on impact and uncertainty were selected to define the scenario logic. These are used as input for the Delphi survey, were experts select the level that each of the three PI dimension reach by the years 2030 and 2040. The reason for these two time periods is to see the evolution path they follow for the next 20 years, considering 2040 as the target goal defined by ALICE. Lastly, the author will derive the evolution of the Port based on the results of the Delphi.



Scenario approach were each contextual scenario gives a particular combination of development of the 3 PI dimensions, and in turn affects the evolution of the port towards the PI Port.

Round 2

For the second round, the previous document outlined above was considered as no longer necessary. Instead, a summarized group response from all 24 respondents from the previous round was shown to them:

Dimensions		Scenario 1					Scenario 2				
		Current State	Level 1	Level 2	Level 3	Level 4	Current State	Level 1	Level 2	Level 3	Level 4
Governance	2030	12,5%	8,3%	**58,3%**	20,8%	0,0%	25,0%	**41,7%**	29,2%	4,2%	0,0%
	2040	0,0%	8,3%	8,3%	**58,3%**	25,0%	4,2%	25,0%	**41,6%**	29,2%	0,0%
Operational	2030	8,3%	16,7%	**66,7%**	8,3%	0,0%	12,5%	16,7%	**54,2%**	16,7%	0,0%
	2040	0,0%	4,2%	8,3%	**66,7%**	20,8%	0,0%	8,3%	33,3%	**37,5%**	20,8%
Digital	2030	8,3%	12,5%	**45,8%**	33,3%	0,0%	16,7%	16,7%	**54,1%**	16,7%	0,0%
	2040	0,0%	4,2%	12,5%	29,1%	**54,2%**	0,0%	16,7%	25,0%	**50,0%**	12,5%

Dimensions		Scenario 3					Scenario 4				
		Current State	Level 1	Level 2	Level 3	Level 4	Current State	Level 1	Level 2	Level 3	Level 4
Governance	2030	**37,5%**	25,0%	**37,5%**	0,0%	0,0%	**37,5%**	33,3%	29,2%	0,0%	0,0%
	2040	8,3%	25,0%	**37,5%**	29,2%	0,0%	12,5%	33,3%	**45,8%**	8,3%	0,0%
Operational	2030	12,5%	37,5%	**41,7%**	8,3%	0,0%	20,8%	**37,5%**	33,3%	8,3%	0,0%
	2040	0,0%	12,5%	**45,8%**	37,5%	4,2%	4,2%	20,8%	**41,7%**	29,2%	4,2%
Digital	2030	8,3%	33,3%	**41,7%**	16,7%	0,0%	20,8%	**41,7%**	37,5%	0,0%	0,0%
	2040	0,0%	4,2%	25,0%	**66,7%**	4,2%	8,2%	12,5%	**41,7%**	37,5%	0,0%

Most voted level(s) per year, for each dimension and year

Example: For Scenario 1, in the Digital dimension, 45,8% of respondents selected, for the year 2030, the Level 2

G. Group response from the Delphi study

Questions		Round 1 (n = 24)					Round 2 (n = 20)				
		CS	Level 1	Level 2	Level 3	Level 4	CS	Level 1	Level 2	Level 3	Level 4
	Scenario 1										
1	Governance (2030)	12,5%	8,3%	58,3%	20,9%	0,0%	0,0%	30,0%	60,0%	10,0%	0,0%
2	Governance (2040)	0,0%	8,3%	8,3%	58,3%	25,0%	5,0%	0,0%	20,0%	65,0%	10,0%
3	Operational (2030)	8,3%	16,7%	66,7%	8,3%	0,0%	0,0%	15,0%	65,0%	20,0%	0,0%
4	Operational (2040)	0,0%	4,2%	8,3%	66,7%	20,8%	0,0%	10,0%	0,0%	75,0%	15,0%
5	Digital (2030)	8,3%	12,5%	45,8%	33,3%	0,0%	0,0%	0,0%	70,0%	30,0%	0,0%
6	Digital (2040)	0,0%	4,2%	12,5%	29,1%	54,2%	0,0%	10,0%	0,0%	35,0%	55,0%
	Scenario 2										
7	Governance (2030)	25,0%	41,7%	29,2%	4,2%	0,0%	25,0%	50,0%	25,0%	0,0%	0,0%
8	Governance (2040)	4,2%	25,0%	41,6%	29,2%	0,0%	10,0%	25,0%	55,0%	10,0%	0,0%
9	Operational (2030)	12,5%	16,7%	54,2%	16,7%	0,0%	5,0%	25,0%	70,0%	0,0%	0,0%
10	Operational (2040)	0,0%	8,3%	33,3%	37,5%	20,8%	0,0%	10,0%	35,0%	55,0%	0,0%
11	Digital (2030)	12,5%	16,7%	54,1%	16,7%	0,0%	0,0%	10,0%	80,0%	10,0%	0,0%
12	Digital (2040)	0,0%	16,7%	25,0%	45,8%	12,5%	5,0%	5,0%	20,0%	65,0%	5,0%
	Scenario 3										
13	Governance (2030)	37,5%	25,0%	37,5%	0,0%	0,0%	30,0%	55,0%	10,0%	5,0%	0,0%
14	Governance (2040)	8,3%	25,0%	37,5%	29,2%	0,0%	10,0%	30,0%	60,0%	0,0%	0,0%
15	Operational (2030)	8,5%	37,5%	41,7%	16,7%	0,0%	10,0%	30,0%	55,0%	5,0%	0,0%
16	Operational (2040)	0,0%	12,5%	45,8%	37,5%	4,2%	5,0%	15,0%	55,0%	25,0%	0,0%
17	Digital (2030)	8,3%	33,3%	41,7%	16,7%	0,0%	5,0%	5,0%	75,0%	15,0%	0,0%
18	Digital (2040)	0,0%	4,2%	25,0%	66,7%	4,2%	0,0%	10,0%	20,0%	70,0%	0,0%
	Scenario 4										
19	Governance (2030)	37,5%	33,3%	29,2%	0,0%	0,0%	55,0%	35,0%	5,0%	5,0%	0,0%
20	Governance (2040)	12,5%	33,3%	45,8%	8,3%	0,0%	10,0%	60,0%	30,0%	0,0%	5,0%
21	Operational (2030)	20,8%	37,5%	33,3%	8,3%	0,0%	15,0%	50,0%	35,0%	0,0%	0,0%
22	Operational (2040)	4,2%	20,8%	41,7%	29,2%	4,2%	5,0%	25,0%	60,0%	10,0%	0,0%
23	Digital (2030)	20,8%	41,7%	37,5%	0,0%	0,0%	10,0%	55,0%	35,0%	0,0%	0,0%
24	Digital (2040)	8,2%	12,5%	41,7%	37,5%	0,0%	0,0%	25,0%	50,0%	25,0%	0,0%

H. Feedback given by the panellists

Adequacy of the two points of time

Asked as a "yes/no" question, experts were given the chance to give their opinions about the adequacy at the end of Round 1. Those who disagreed (chose "no" to the question below) could argument their selection. The anonymous 2 responses are presented in the table below.

"Do you think it was a good idea to include two points in time (2030 and 2040)?"

Respondent n.2: *"Hard to predict pace of developments."*
Respondent n.5: *"It is difficult to think of 2040 from now and to predict a non-linear future."*

Scenario description

Asked as a "yes/no" question, experts were given the chance to give their opinions about the detail of scenarios provided during the Delphi at the end of Round 2. Those who disagreed (chose "no" to the question below) could argument their selection, which are the following:

"Do you think the scenarios were detailed enough?"

Respondent n.5: *"Still not too convinced about the order of the different levels, making it challenging to select an answer."*
Respondent n.9: *"The differences between scenarios are not fully clear for me. From my point of view there is a strong link between regulatory frameworks and protectionism, especially if you look at regional, national or global level."*
Respondent n.10: *"The topic is by far too complex as to describe it in this few sentences and there are more options to be considered."*
Respondent n.14: *"The dimensions (governance, operations, digitalization) are not independent and have different impacts on any future developments. Digitalization is the easiest to achieve, operations is harder, but governance is extremely difficult. This is not clearly posited in the scenario descriptions."*
Respondent n.19: *"Questions don't allow to consider the conditions that are different even in the various EU countries and areas. This is not realistic, as the initial status is not the same everywhere."*

Delphi survey

A final open question was asked at the end of Round 2. It aimed to collect any other comment or opinion not given before concerning the Delphi survey.

"Any other comments on the Delphi methodology in general?"

Respondent n.2: *"Some room for additional explanations (to show reasoning behind scores) would have been nice."*
Respondent n.5: *"The phrasing of the scenarios already implies the "right" answer."*
Respondent n.12: *"It would have been nice to read some arguments from other participants about why they opted for a certain choice."*
Respondent n.14: *"You collect opinions, our visions about the future. Expert advice is valuable if it mines the experience. Visionary opinion, even if from experts, is risky as a basis to build any knowledge, because there is no possibility for validation. On the other hand, it gives a valuable insight on the level of skepticism (or optimism) of PI thinkers. Which is an interesting result by itself, but still, it remains everybody's guess about what the future will bring."*
Respondent n.15: *"Nice survey!"*

PI Port framework

In the following question, asked in the Round 1, 12 people out of the 24 responses gave feedback regarding the resulting PI Port framework from Chapter 3.

"Any comments on the conceptualization of the PI Port proposed in this survey?"

Respondent n.1: *"Please also consider an open dialog between ports and port cities. In addition, views for achieving a safer, securer, more efficient and low carbon footprint ports and port cities of the future shall be considered. A good understanding of the intelligent hubs (ports and port cities), and the local and international freight transport network, including inland transport (road, waterway, rail and pipelines) and how it can contribute towards establishing a mutually beneficial relation between relevant actors (such as port and city authorities, terminal operators, intermodal infrastructure providers, Logistics Services Providers, ICT companies and end users) shall be considered."*

Respondent n.3: *"Some dimensions and characteristics lend themselves better for "to what extent" questions rather than yes/no"*

Respondent n.4: *"Sometimes, it seems easier to achieve level 2 (connect terminals) than level 1 (integrate supply chains). Same holds for automating cross-docking operations and synchromodality. "*

Respondent n.5: *"I am surprised by the high focus on regulations. It is my experience that the general culture in Maritime Ports (traditional not interested in cargo movements beyond the maritime leg) and the various competitive pressures (which are different for the different stakeholders e.g. ports and shipping lines) influence decision making in this environment more than regulation."*

Respondent n.6: *"The different scenarios will most probably lead to different developments which were not mentioned in the "Level-boxes"*

Respondent n.8: *"Global trade developments do not have that much impact on local developments (ports or port regions)"*

Respondent n.14: *"A further evolution level between 3 and 4 could be useful. Jumping directly from intra-EU to the global dimension could be too much... (macro-regions still play an important role when you think about ports, as some European ports do serve destinations outside EU but in their macro-regions)."*

Respondent n.15: *"You might argue that intra port reshuffling in the operational setting could be less difficult than achieving full synchromodality in the hinterland. In other words you might see containers moving between terminals in a port earlier than true synchromodal operations across several operators.*

Respondent n.18: *"I have some major issues with the model. It is all around ports with terminals operating as hubs. We have to take a data perspective. Data is the source to optimize decisions by algorithms; various stakeholders can develop and others can operate these algorithms. We see them already coming in PortCDM and the Global Digital Container Alliance of shipping lines. What is thus most important is to construct a model that includes data sovereignty and legal aspects, focusing on two timelines and taking different perspectives. For instance, the EU can have regulations that particular data cannot be shared outside its boundaries and is only accessible to EU registered companies, thus protecting their internal market."*

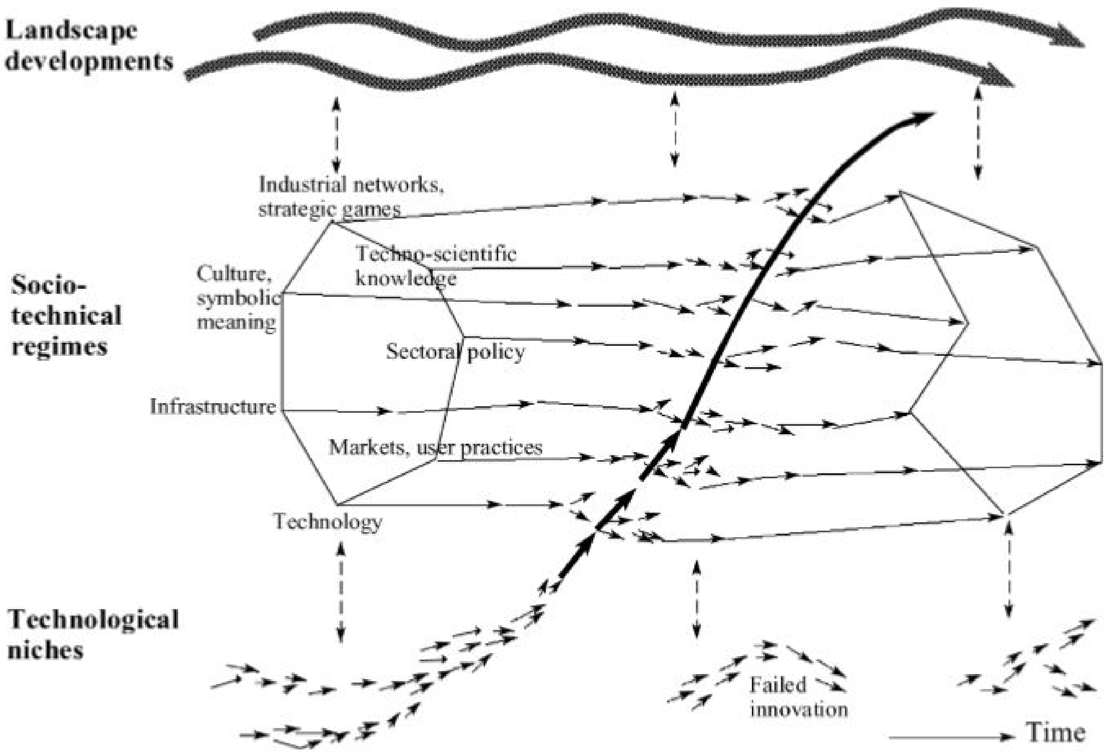
Respondent n.20: *"All in all a challenging prospect to think about the various scenarios although I personally think that the main differentiator is indeed the global level of protectionism that might be a slowing factor on the implementation of the FULL concept of PI. However I think that Level 3 is the more realistic ambition for 2040 and that the Original timeline set out earlier in ALICE of 2050 still stands... even though ALICE advanced it to include the zero-emission objective of the EU."*

Respondent n.24: *"For me, it is clear that the governance aspect is the most difficult to tackle for achieving the envisaged progress levels (in all scenarios). The digital is the easiest, and the operational comes in the middle. I would add this "prioritization" scheme to the framework."*

I. Technological Transition framework

The Technological Transition (TT) model by Geels (2002) has been mentioned in some stages of the thesis. The model, which brings together insights from evolutionary economics and technology studies, is a theoretically-grounded framework that shows the evolution, from niche to a regime level, of a particular technological innovation, which can transform the way societal functions are fulfilled, in the context of "socio-technical regimes" and "landscape developments". The former, being defined as the "semi-coherent set of rules carried by different social groups", functions as a selection or retention mechanism of a particular "radical" innovation, which break the *status quo* of a particular regime. The later in turns refers to external factors that evolve at a slow pace, such as political or demographic trends. Examples of recent radical innovations within transport could be blockchain, Hyperloop or autonomous vehicles.

It is important to note that this model deals with a particular technological innovation, whereas the Physical Internet is considered as "a myriad of components that [...] through their well-designed relationships and inter-dependencies, the system (PI) as a whole can achieve its purpose completely" (B. Montreuil, Meller, & Ballot, 2012). Therefore, the applicability of this framework to the entire PI could not be realistic. Yet, by breaking down those different PI dimensions, which entail technological innovations, into smaller components, the use o the TT framework from Geels (2002) could potentially become more suitable.



Technological Transition (TT) framework by Geels (2002).

J. General reflection on the thesis

I remember when I started this final thesis six months ago, in February of 2019. I was juggling between the end of my previous work, the *TIL 5050-12 Interdisciplinary Project*, which had kept me quite busy for four months at KLM, and the kick-off meeting of my thesis. From the intense work at the Dutch airline, from which I could not have the week break that all students well deserve in February, I was mentally burnt out and not ready to embark in a master thesis which seemed back then long, exhaustive and vague.

I must admit now that I accepted the thesis that Patrick offered me basically because of the combination of the words "Physical Internet" and "Port of Rotterdam", which deeply attracted me. All this without really thinking about what the research truly entailed. Not surprisingly, that first reunion with my thesis supervisors did not go very well. With an unclear methodology, contradicting concepts and not really understanding the outcome they wanted from my thesis back then (I had no idea what I had to do to be honest), the feedback was quite clear. "Maybe it is a bit too early to start your thesis", said one of the supervisors.

"This is going to be a tough one", I said to myself several times. Perhaps I should have taken a month to pause, take a step back and try to start over fresh. Yet, maybe it was my desire to finish my studies on time, and therefore avoid paying more tuition, or my pursue to reach the Cum Laude distinction, or a combination of both. Truth is, I decided to get on to work immediately, reformulating my approach while diving into the literature. The feeling is basically like falling into the middle of the ocean (I do not wish this to anyone), swimming around circles, and at some point saying "screw it, I am going this way", and just hope to find land. It took several meetings with professors and calls with Patrick, who was working overseas at Georgia Tech among some of the most erudite scholars in the field of PI. After several iterations, papers read and almost a mental breakdown, I had an "approach" that people somewhat agreed to. I was off to start a thesis with a lot of uncertainties, trying to merge two topics that had been unexplored before, a feeling that relates quite well to the topic of my thesis.

My first goal was to grasp the knowledge of the PI from literature. Its young stage made it quite hard to conceptualize. It is true that the body of literature is currently limited. The problem came from the fact that there is no strong consensus on what the Physical Internet is. After almost two months, together with Jeff, we managed to come to a valid idea of the PI which could be further used for the interviews with the experts.

With our own vision of the PI, we conducted calls and in-person interviews with experts, which included travelling once for three hours to Groningen. They were something different to what I was used to do as an engineering student, and not as straightforward as I initially thought. We did very little planning for the consultations, and purposely allowed the experts from the beginning to stir the discussion in the direction they wanted. Albeit being sometimes tiresome for both interviewers and interviewees, I think they were an enriching experience, not just for the research, but also to get to meet interesting people in the field. I must admit that at this point, our supervisor Prof. Tavasszy was really helpful, who agreed to meet with us more than once, to help us merge everything into one big picture. Terminology was a big challenge, considering that each defined elements, concepts or characteristics of the PI differently. It was the beginning of May and we had realized we had a framework which we could both use for our own next stages. Later on did we find how proud we should be to be able to have been able to reach this point, considering that many students had failed to continue with PI research in previous theses.

The Delphi was another interesting experience. I had to create a survey, send it out to experts, and receive their answers in two rounds, and *"klaar is kees"* (something like "that was it" in Dutch). It seems quite straightforward at first sight. Yet, there were many factors which you would not think about initially, which nevertheless turned out to be crucial for a successful outcome. Summer was around the corner, and many of those experts usually receive hundreds of e-mails on a daily basis. Therefore, non-response was a big concern for me. I had to speed up the process to choose an online tool and design the questionnaire. All this while reaching out on LinkedIn to experts in the field and asking them about availability, with the hope to make them aware of the fact that, at some point, they would receive an invitation to participate in an online survey, and that they would need to fill it in in no more than two weeks. With the help of Patrick, who knew many of them personally, we managed to get a pretty decent response rate. Much higher than what I initially had in mind when I first heard about the Delphi I would need to conduct.

Those who have interacted with me throughout the last six months know how much I struggled with this thesis. I embarked in a very hard topic, in a context still unknown within the academic community, and with a heuristic methodology that was unfamiliar for me at the beginning. Yet, I successfully managed to arrive at something very similar to the outcome initially expected by my supervisors at the beginning of my thesis. As far as I know, this is the first time a Delphi study is conducted ever in the field of PI. Maybe it was my engineering mindset (a capacity of "learning to learn"), my stubbornness to get things done no matter the difficulty, group thinking with Jeff or Patrick, luck, or a combination of all of the previous. Truth is, I am really happy with the final results I have arrived at in six months.

Looking back in time, it is interesting to see how my approach has evolved from February, the moment in which I was swimming in circles in the middle of the ocean, until now, when I reached land. An unknown land for the scientific community, which opens room for further research and debate. I sincerely hope the findings presented in this thesis will make a meaningful contribution to the compelling vision of the Physical Internet.

K. Scientific Paper

The scientific paper herein presented discusses part of the complete research that has been conducted throughout this master thesis, and is adapted to the current body of futures literature. In particular, this paper is positioned around transport scenarios studies, proposing a Delphi study to generate what the author refers to as "PI scenarios", opening room for a new stream of research and debate around the Physical Internet and maritime ports.

Exploring the future of ports in the Physical Internet: A Delphi study

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Abstract

The Physical Internet (PI) is a novel vision that aims to reshape and improve efficiency of transport and logistics. A game-changing vision is expected to have a profound effect on all actors involved in freight transport systems. However, the concept is still in early stages, and the study of the PI in the context of maritime ports has remained unexplored. With maritime ports considered as key global trade enablers, the proposed research aims to provide insights into possible scenarios for the evolution of ports under the development of the Physical Internet. Firstly, a framework that shows the categorical evolution of ports under the influence of three developing PI characteristics is generated, by means of literature review, interviews with experts and brainstorming sessions. Secondly, a scenario logic approach is used to generate hypothetical futures. Both the framework and the hypothetical futures are then used as input for a Delphi-study in which experts in the field of PI assess the level of development of each of the PI characteristics for the years 2030 and 2040. The results from the questionnaire are used to generate the evolution path of maritime ports through the lenses of the proposed framework, for each scenario. An important finding from the survey is that a governance dimension, which entail a set of rules and protocols for a cooperative, safe and reliable PI environment, can lag behind and delay the development of ports towards ”PI ports” in the upcoming years. Also, under the most optimistic scenario, the Physical Internet scales up to the regional level at most by the horizon year 2040, with ports not reaching the level of global hub hyperconnectivity by this period, as per the opinions of the PI experts.

Keywords: Physical Internet, maritime ports, scenarios, Delphi, freight transport

1. Introduction

In the past century, 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 [32]. 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. Therefore not only functioning as nodes of the transport network, but also as a location of industrial and value-added logistics activities [57]. With ports being highly asset and capital intensive [67], coping with future uncertainties is crucial so that port authorities can determine appropriate strategies and justify proper investments, which have long payback periods. In this sense, failing to respond to potential changes and developments in transport 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 [28]. In order to deal with these uncertainties, a common practice is to develop scenarios [45]. Scenarios are defined as ”consistent and coherent descriptions of alternative hypothetical futures that reflect different perspectives on past, present, and future developments, which can serve as a basis for action” [87].

At the basis of this research lines young and recent concept that aims to reshape the way physical objects are currently moved, stored, realized, supplied and used, and is called the Physical Internet (PI) [51]. It was formally defined by Montreuil et al. [52] as an ”open global logistics system founded on physical, digital and operational interconnectivity through encapsulation, interfaces and protocols”. Because of the complexity and the change in paradigm it implies [51], an idea of this magni-

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tude is expected to have a profound impact on all actors involved in freight transport systems in the future. Hence, albeit beind identified by many stakeholders as a promising vision for a more efficient transport and logistics system, the concept is currently in its infancy and many questions still need to be answered.

The introduction of the PI sparked research collaborations among academia, industry and governmental institutions to progressively share and develop knowledge on the topic. With 80% of the total share of global trade being done over sea [85],the maritime transport system is expected to be significantly affected. In this sense, maritime ports as they are known today could profoundly change over time under the influence of the PI.

Despite its potential significant implications, the study of the PI in the context of maritime ports has remained, to the best of the authors' knowledge, nearly unexplored. This raises questions about the way ports will function under PI freight transport systems. In line with this, possible future developments of the PI, which in turn can influence the evolution of ports, have not yet been investigated in current literature. As a result, port authorities do not have the necessary knowledge to effectively anticipate, with strategic decisions, the way global maritime freight systems can develop in the context of the PI.

The primary objective of this paper is to generate scenarios for the evolution of maritime ports under the development of the PI, referred to as "PI scenarios" in this research. The main research question addressed in this paper is therefore "what are the scenarios for the development of maritime ports under the Physical Internet?". Experts' opinion are suggested as the most reliable element available when facing an uncertain future [23]. One common technique in future transport scenario studies of qualitative nature is the Delphi method [45]. It allows for a systematic solicitation of anonymous informed judgements on a particular topic through a multistage survey process, where feedback of group opinion is provided after each round [see [83]; [27]; [26]]. A secondary objective is to derive implications for strategic decision making of port authorities.

In this paper, alternative hypothetical futures situations are constructed and then translated, through a Delphi study, to a set of scenarios that outline the development of the main PI characteristics which in turn result in the the evolution path of maritime ports towards PI-based ports, referred to here as "PI ports".

There are several contributions of this paper. Firstly, to identify a range of potential futures of the PI. Secondly, to visualize the evolution of maritime ports in the PI, herewith opening room for an enriched debate around maritime ports in the PI. Thirdly, to provide managerial implications resulting from the PI scenarios as a starting point for port authorities to consider, in their strategic decision making, the influence of PI in maritime freight transport systems.

The rest of the paper is organized as follows. Section 2 dives into the different streams of literature used in this research, namely in the fields of the PI, port development and scenarios development, from which the literature gap is identified. In Section 3, the methodological approach of the Delphi is outlined. Section 4 discusses the results of the Delphi and presents the different PI scenarios and the implications for maritime ports. Section 5 concludes the paper, providing general recommendations for port authorities and further research.

2. Literature review

2.1. The Physical Internet (PI)

First mentioned in the domain of logistics in June of 2006 on the front page of The Economists [42], the term PI was not further elaborated upon until the first formal scientific work coming from Prof. Montreuil, the major visionary of the PI. Thirteen symptoms related to current supply chain and logistics practices were exposed, which result in economical, environmental and societal issues that, according to the author, needed to be addressed to avoid "hitting the wall" [49].

The PI was presented as a potential solution to address these issues. In short, the PI aims to organize the transport of goods similar to the way data packages flow in the Digital Internet (DI) [5]. In this case, the DI is broadly defined as a system of interconnected IT networks based on a set of standardized networks [6]. Through sharing of resources such as assets and data, and the design of interfaces and protocols for seamless "interoperability", the transport of goods under the PI are optimized with regard to costs, speed, efficiency and sustainability. As in the Digital Internet, where fragmented packets are automatically sent through different routers, goods could be encapsulated in modular containers and be sent throughout a networks of open hubs towards their final destination [4].

The introduction of the PI was a call for action for academics, industry and governtal institutions. Following the main foundations of the PI, whose components highly stem from technological innovation [52], several publications worked on different levels of abstraction and methodologies. A first simulation study, based on product distribution flow of two main food retailers from their top 100 suppliers in France, showed inspiring results about the potential of the PI. Cost savings ranged from 4% to 26%, aside from a threefold reduction in greenhouse gas emissions in comparison with traditional dedicated network models [5]. Conceptual designs of different type of hubs in the PI were addressed in [46], [7], and [53]. A framework linking the concepts of City Logistics and the PI was proposed by [17]. The layered structured from which the DI protocols work were adapted to a PI context in [50] and [15]. The analogies between the DI and PI hubs were also studied [70]. Business models, as well as new regulatory frameworks have also been targeted as an important issue to address in this new logistics paradigm [54]. Other publications worked on mathematical models that ranged from standardized container selection [40], to dispatch models [89]. Further simulation studies were also conducted on different levels of transport and logistics (see [61]; [68]; [69]; [35]). An engineering design approach was also applied to propose a prototype of PI unit loads [36]. In more recent years, critical literature reviews appeared to try to bring in together all the increasing body of knowledge created around the PI and set robust research agendas for the future (see [81]; [77]). Up to sixth editions of the annual International Physical Internet Conference (IPIC) have been celebrated to gather experts internationally and encourage knowledge sharing and building on the young topic [31]. On European level, under the so-called ALICE initiative, regular meetings and workshops are organized to reach consensus around the PI vision and the next steps it needs to undergo in the implementation of the overall vision [2].

2.2. *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 [9]. Ports have initially been categorized by the UNCTAD into "port generations" or stages as an explanation of how these have adapted to incorporate technological, political and operational changes over time. Three generations were proposed, which evolved from traditional (un-)loading activities (first generation) to a wider range of logistics and value-added activities (third generation) and considered as a product of global containerization and globalization (see [8]; [62]). A fourth stage (4GP) was added in 1999 by the UNCTAD, "which are physically separated but linked through common operators or through a common administration" [86]. Academics have given however different interpretations to what the 4GP entailed (see [60]; [90]). A fifth generation ports model (5GP) was proposed as "customer-centric and community focused ports, with service deliverables related to port user's multifaceted business requirements, while also taking care of community stakeholder requirements" [25]. Building upon the previous, a modified version of the concept from the 5GP was presented to evaluate interport competition of major ports in Asia [38].

The UNCTAD approach has been subject to criticism. The generation approach generally fails to reflect the composite reality of seaports by applying a rigid categorization. Fourth generation ports can still be performing first generation-type functions by handling first generation-type cargo and ships (see [9]; [90]). Others concluded that the UNCTAD model was fundamentally flawed [8]. Differential development can take place at individual terminals within a port, as a result of commercial pressures or goals of the different actors. Moreover, the allocation of ports to a particular generation category might be problematic, since "all ports are, to some extent, unique". Likewise, "rather than in discrete steps, ports evolve continuously" and adapt to their external environment by continuously changing economic and trading patterns, new technologies, legislation, and port governance systems. Developing continuous steps for port next generation models remains challenging, and a framework in which port generations evolve along a "port ladder" describing how leading ports are continuously adapting to new customer requirements, in line with an ever changing shipping and port environment, was presented [37].

The development of ports could be also seen in phases from a spatial perspective. A well known framework is the "Anyport" model proposed in [10]. In an initial stage, a small port site evolves as a product of evolving maritime technologies and improvements in cargo handling. In this sense, setting, expansion and specialization are the three major steps identified in the port development process. For large traditional ports, the model has been considered a valid interpretation of port development. Nevertheless, weaknesses were identified in this framework, such as the lack to include the inland dimension as a driving force in the dynamics of port development [59]. As a result, a phase of port regionalization was added and built upon the Anyport model, whereby the influence of the port extends beyond the port boundary by means of broader strategies which link the port to a wider market. The "gradual and market-driven" formation of a "regional load centre network" is the result of increased focus on inland accessibility, as the cornerstone of port competitiveness, and higher levels of integration between both maritime and inland transport systems [29]. The formation of a port region, defined as a "port system or a system of two or more ports located in proximity within a given area", was also acknowledged in a study of evolving roles of ports in the globalized world [43]. Port regions can vary in function and importance with respect to the traffic specialization and the continental context in which they play. Eight types of port regions were identified in [22]. One being the "Metropolitan" typology, where port regions, such as the Hamburg-Le Havre range, are considered to be "richer, more densely populated and more service-oriented with lesser production activities, but handling more general cargo".

2.3. Scenario development

Scenario development has notably evolved since its military origins following the end of World War II, and scenario typologies have been proposed to make the field of futures studies easier to overview (see [33]; [73]; [41]; [88]; [21]). Accepted by many academics is the scenario typology proposed by Börjeson et al. [11], who distinguished between three main 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?"). The difference between normative and descriptive scenarios lays in the aim to reach a particular point in the future (normative) or to simply outline possible futures without indication of desirability (descriptive) [87]. Explorative scenarios could also be considered as contextual scenarios, which "provide images of possible future environments of the system to be taken into account, which focus on the environment that cannot be inuenced by the policymaker" [24].

To construct scenarios, qualitative or quantitative inputs can be used [87]. Qualititative input is appropriate for high levels of uncertainty, where relevant information cannot be quantified. In this case, participatory approaches are used [see [24]; [11]]. Quantitative input is appropriate whenever information can be accurately quantified, so that computer models such as scenario discovery can be used [28].

The use of scenarios as a basis for strategic decision making is not new. The Dutch/British company Shell has been extensively working on oil forecasts since the 1970s, which allowed them to adapt better to sudden fluctuations [71]. Another example is the study of global scenarios, by means of an economic forecast model, presented in 1999 by the Dutch Bureau for Economic Policy Analysis. Scenario discovery, a model-based approach, has been used to assess potential vulnerabilities for the port of Rotterdam [28]. Delphi-based scenarios for the logistics futures in Europe, with over 200 experts from six different countries, were elaborated [16]. Three scenarios were generated using a similar methodology to assess the carbon footprint of freight transport in the UK for 2020 [63]. An extensive Delphi-based scenario study on the future of logistics services industry for the year 2025 was also elaborated [27]. Many other examples of participatory approaches, with Delphi as a common method, can be found in transport futures literature (see [80]; [78]; [74]; [44]; [72]; [82]; [39]).

2.4. Literature gap

From the literature review provided above, the following conclusions can be derived. Firstly, there is nearly no literature linking maritime ports and the PI. Only one publication, building upon the analogies between the DI and PI hubs, has been found to link the role of seaports as "hyperconnected PI hubs" from an operational perspective [4]. Secondly, the development of the PI has been recently explored in the SENSE workshops. Nevertheless, no scenario studies have been found regarding its evolution in scientific literature. This paper is a first step to fill relevant and significant literature gaps, opening room for insightful research around the exploration of development paths of the PI and maritime ports.

3. Research approach and methodology

Since its introduction by the RAND corporation around the late 1950s [18], the use and number of different types of Delphi studies has grown, from the traditional method to the round-less Real Time Delphi [45]. In this paper, the Delphi process employed is based on the classic procedure, which is among the most approved variants of the Delphi [27]. However, the originality of the Delphi technique applied here stemmed from the information provided to the panel members. Considering the terminology proposed in [11], explorative or contextual scenarios were suitable for this research, given the qualitative nature of the exercise and the levels of uncertainty around the PI. Rather than using a Delphi study to develop them, a scenario logic approach was used instead [24]. The resulting contextual scenarios were in turn used, together with the evolution levels of the different main PI characteristics that result from a proposed "PI port framework" on a five-point scale, which will be elaborated upon later in the paper, as input for a Delphi study. Panellists had to select how far each of the PI characteristics would reach for a particular period of time, for each contextual scenario. The outcomes from the Delphi were used, together with the framework, to generate a set of PI scenarios that depicted the evolution path of the port towards a PI Port, as a function of the development of the PI characteristics, for each PI scenario. Figure 1 illustrates the individual stages

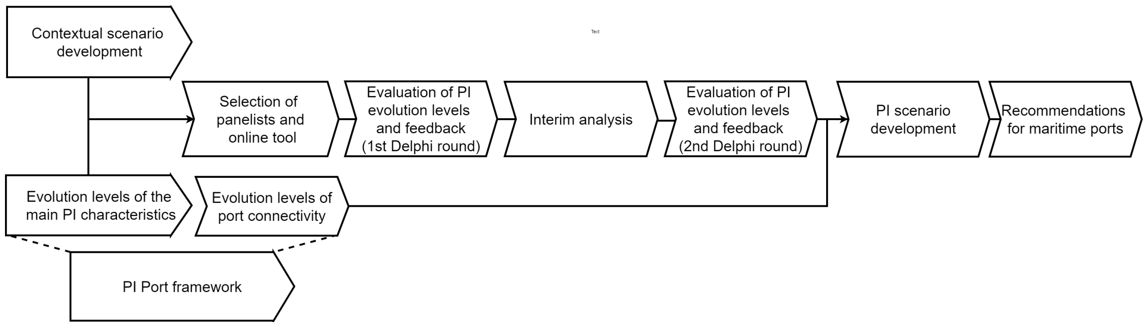

Figure 1: Process of PI scenario development proposed in this research.

of the research and shows how the Delphi method was used to generate the PI scenarios.

One of the main disadvantages in Delphi studies is the difficulty to keep respondents motivated during consecutive rounds. Low response or non-response can become a common problem [see [30]; [27] or [76]], mainly due to excessive length of questionnaires and number of rounds. Two Delphi rounds were conducted only, with the goal to keep fatigue among panellists as low as possible, which in turn is expected to yield a higher response rate and validity of data [48]. Applying a Delphi method to also generate contextual scenarios would have needed additional rounds and would have made the entire study even more time consuming for the panel members. Hence, to avoid the aforementioned reduction in response rate and reduce fatigue of panel members, in this paper we deployed a scenario logic approach, a less demanding approach from a respondents' perspective and yet a valid and frequently applied method to develop contextual scenarios [24]. Next, we deployed a two-round Delphi on the the development of the PI for each of the resulting contextual scenarios.

Accounting for all uncertainties within the global logistics system could lead to generating a massive number of scenarios [28]. Yet, the paper aimed for a set ranging between 3 and 8 scenarios, based on the recommendations and outcomes of other transport scenario studies (see [12]; [82]; [45]). Additionally, for validity purposes, around 45 days for the entire Delphi study, and at least 12 panel responses per round, were aimed for in this research, according to the guidelines from Delphi literature (see [48]; [30]; [24]).

In view of the goal of the European Commission-based ALICE project to reach the PI by 2040 [1], a planning horizon of about 20 years was chosen for the Delphi. This length of time would give panellists enough room to think creatively and get "out-of-the-box" [27]. To allow a visualization of a non-linear path from the present, the intermediate year 2030 was also considered for the study. The following sections provide a more detailed explanation of the research methodology and approach of this paper.

3.1. Evolution levels of the main PI characteristics

The first step to construct the Delphi questionnaire was to elaborate a categorical scale in which the main PI characteristics evolve. To determine these, a more in-depth literature review of the PI was considered. The sources of information came from academic papers, conference proceedings, lectures or seminars published online (i.e. Physical Internet Center), as well as white papers. Only publications in English were considered, and master theses were excluded. Electronic databases for the academic search was Google Scholar, in combination with the digital library of the TU Delft. The search string to identify relevant studies was "Physical Internet", and only published papers prior to March of 2019 were considered. Abstracts were read to make a content check, and the selected publications were categorized according to the methodology applied.

A total of 41 publications were selected, including those already mentioned in Section 2.1. For validation purposes, a comparison was made with a systematic literature review of the PI from [77]. Out of 46 publications, 26 were selected in both reviews, including the most cited papers in the PI (see [51];[49]; [52]). The main characteristics from the selected publications were identified as "the means to an end" [52] through a counting technique.

The findings from the literature review were then complemented with interviews with experts in the PI. To select candidates, an expert selection criteria was followed. This referred mainly to having *"substantial knowledge of a certain field"* [24], which was translated in this research to comply with any of the following: (1) having published papers or conducted academic lectures on the PI; (2) having participated in workshops or any other type of event related to the PI; (3) having supervised academic projects about the PI. A total of 4 interviews were conducted, with experts located in the Netherlands,

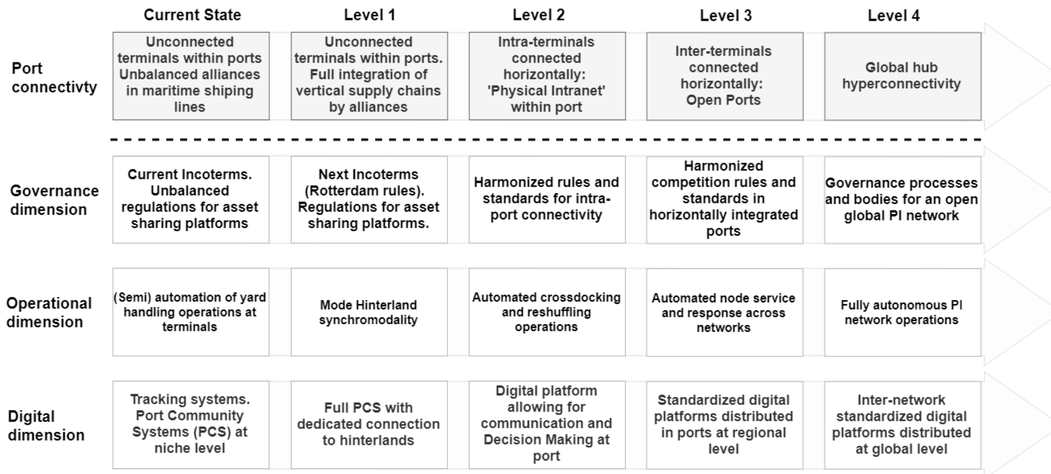

Figure 2: Resulting PI Port framework, with evolution levels on a categorical five-point scale.

Germany and the United States. Albeit being the number of consultations seemingly low, their relevance and contribution in the field of PI made them suitable experts. Moreover, they spoke on behalf of larger communities of experts, both in the US and Europe, and for these reasons, their opinions were considered to be sufficient. The interviews followed an unstructured format, to allow experts to freely express their opinions and avoid bias from the interviewers. The purpose was to ask them for feedback about the outcomes of the findings from the literature review, and what they considered to be the main PI characteristics and external factors affecting their evolution.

Considering the different levels of abstraction found from both literature and interviews, and the lack of consensus in the terminology used in the PI, all the identified characteristics were clustered into three distinct overall dimensions through a brainstorming session, which included one of the experts. These captured a general idea of the PI while keeping the number of characteristics reduced, which could therefore mitigate the fatigue among panellists during the Delphi. The three dimensions are the following:

- *Governance dimension*. This layer refers to the set of rules and protocols for a cooperative, safe and reliable PI environment.
- *Operational dimension*. How transport is physically executed and operated by the different elements in the transport network, from hubs, warehouses, vehicles or handling equipment, is considered in this dimension.
- *Digital dimension*. This dimension deals with the physical connectivity of the different players in the logistics network. A system is in place so that actors can share information, communicate and make decisions for an optimized transport network.

Based on the previous generalized idea of the PI, the same three dimensions were tailored to the context of maritime ports as nodes in transport networks. After several brainstorming sessions, and taking the "PI generations" approach from the SENSE project [3] and the Digital Maturity Model proposed by the port of Rotterdam [64] as background, an evolutionary PI port framework was generated. The bottom-up model, presented in Figure 2, captures how the previous three PI characteristics, or dimensions, develop and influence the evolution of a port towards a hyperconnected maritime port, or PI Port. Within the proposed *governance dimension*, the current scattered standards and reactive Incoterm rules are replaced by the upcoming Rotterdam Rules, and progressively evolve to the implementation of governance bodies for an open global PI network. These respect the sovereignty and integrity of different nodes, ensuring seamless, secure and confidential exchange of goods, data and assets. Moreover, the maritime "Consortia Block Exemption Regulation" (CBER) currently allows, under certain conditions, shipping lines to enter into cooperation agreements to provide joint cargo transport services. Such antitrust exemption of Article 101 of the Treaty of the Functioning of the European Union (TFEU) expires in April of 2020. The decision to expire or extend it is currently under consultation, Regarding the *operational dimension*, semi-automation of yard handling operations evolve over time into complete autonomous operations within the port domains, exploiting the benefits of open networks. Lastly, within the *digital dimension*, current tracking systems at niche level evolve all the way to standardized digital platforms that allow for digital connectivity among the different networks. Port "connectivity" jumps upward, from the Current State, whenever the three dimensions have done so. First within the port level, becoming open internally (Level 2 with open terminals or "Physical Intranets"), then becomes open with other ports within the same region that have made the same transition (Level 3), and finally scales up to the so-called "global hub hyperconnectivity" , with all ports PI ports (Level 4). The last stage could be seen as the formal definition of the PI [52], and by showing an evolutionary path, the proposed framework tries to break the misconception, already identified in [81], that there is a "binary state in which the PI either exists or not". Instead, the PI dimensions, and therefore port connectivity can evolve in a ladder, as in [37], with the vertical integration of supply chains being developed before horizontal integration of networks. The term "connectivity" was considered broadly from the three proposed dimensions, with hyperconnectivity as a popularized statement within the PI community that refers to the highest level of connectivity.

3.2. Development of contextual scenarios

An scenario logic approach was used to develop a set of contextual scenarios [24]. Contextual factors, defined as "variables that influence the development of the system but that cannot be influenced by the problem owners themselves", were identified through desk research, which included academic publications (see [58]; [75]; [79]) as well as reports of future trends in transport from companies and institutions (see [20], [55] ;[56]; [91], [65], [66]), the previous interviews and brainstorming sessions. The *"system"* in this case was considered to be the resulting PI Port framework outlined in Figure 2, and was strictly defined for methodological purposes as *"the evolution of three PI dimensions which influence the development of the port towards a PI port"*. The "problem owner" in turn was the port of Rotterdam. The contextual factors were then clustered into a set of driving forces, through a brainstorming session and logic reasoning. A first filtering was done on those contextual factors that could not clearly be allocated to a particular driving force, or were overlapping with other contextual factors. The PESTEL (political, economic, societal, technological, environmental and legal) framework was not considered strictly with the purpose to avoid rigidity and isolate a contextual factor to one particular PESTEL dimension only [14]. This was done at the cost of potentially encountering strong interdependencies (non-orthogonality) of the driving forces.

A total of 32 contextual factors were identified and clustered into 7 driving forces. These were "global institutional integration"; "flow patterns"; "climate change"; "technological innovations"; "regulatory frameworks"; "business models"; and "demographic changes". The driving forces with the highest level of uncertainty (*"there is a clear development path or direction of this driving force or not"*) and impact on the system (*"this driving force has a clear impact on the evolution of the evolution of the three PI dimensions from the proposed framework or not"*) were further selected as relevant to draw the skeleton that spans the scenario logic. The impact-uncertainty assessment was done through desk research and logic reasoning. An orthogonality check was not strictly conducted, and the 7 driving forces were not completely independent from each other. For that reason, besides assessing the impact-uncertainty of each of them individually, the goal was to arrive at a final set of relevant driving forces that would not fully influence each other. In other words, a selected driving force should be allowed to freely move, to a large extend, in one direction or another, regardless of the development of another selected relevant driving force.

From the assessment, "global institutional integration" and "regulatory frameworks" were considered as the most relevant. It would seem reasonable to consider the former influencing the later. Yet, with the framework founded on the economics of institutions from Williamson [92] as background, it was argued that their developments, since they evolve in different time frequencies, were not fully dependent from one another.

For the case of "global institutional integration", the driving force could develop in a direction towards globalization worldwide (+) or to an global environment of high protectionism between major power blows (-). For the case of "regulatory frameworks", the focus was narrowed to either fast technology-enabling regulatory framework that adapt to market developments (+), or slow regulatory frameworks lagging behind market developments (-). The combination of opposing developments of the driving forces outlined four contextual scenarios in total. While acknowledging that a small final set of scenarios might not summarize the full breath of uncertainty about the future [13], four scenarios goes in hand with the recommendations from transport futures studies already mentioned.

3.3. Selection of experts and online tool

The criteria of *"substantial knowledge of a certain field"* [24] was also used to select suitable candidates. Potential panellists were identified from online publications (i.e. papers or lectures) and workshops (i.e. SENSE or IPIC) related to the PI. Moreover, it was assumed that having knowledge in the PI, which entails transport and logistics in general, was enough to consider a candidate as knowledgeable in maritime ports. Two weeks before sending out the first round, potential candidates that met the

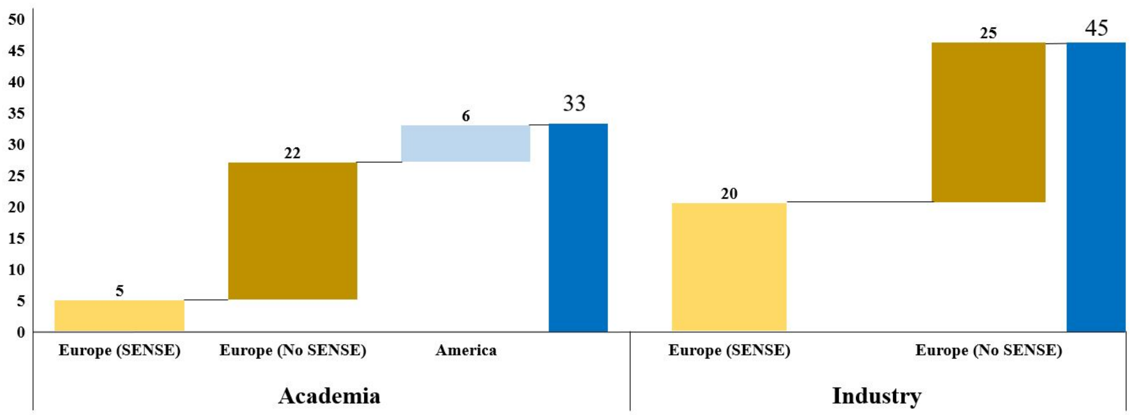

Figure 3: Characterization of potential candidates based on sector and geographical location.

criteria were contacted. They were briefly presented with the purpose of the survey, the role that participants needed to play, and finally asked for availability. Those who did not clearly state an unwillingness to participate in the survey were considered as suitable candidates. Skepticism was visible from some of the subjects, with comments such as ”my is limited” or ”how long will it take?”. This already gave an early indication that the information presented in the survey, and the questionnaire itself, would have to be as clear and concise as possible, so that potential fatigue could be mitigated as much as possible.

In total, 78 subjects were identified as suitable candidates. 33 coming from research institutions (universities), while the remaining 45 coming from industry. The majority of the candidates came from Europe (72), and belonged to both academia (27) and industry (45). The other 6 candidates, all from academia, were located in North America (5 in the US and 1 in Canada). Up to 25 members of the SENSE project were identified within the European group. From these, 5 belonged to academia and the remaining 20 to industry. Figure 3 shows a breakdown of the potential candidates that received the Delphi questionnaire.

In parallel with the selection of candidates, an online survey platform was chosen for the Delphi study. The platform typeform® was found to be an user-friendly survey tool to conduct the questionnaire with experts located geographically apart. Its major drawback was its rigidity. It did not allow for communication in real time between the panel members and the researchers of this paper, and therefore potential misunderstandings, especially during the first round, could not be solved. Moreover, the length of the description of each of the four contextual scenarios was limited to the size of the interface. Questions were designed in a five-point scale format, totalling 24 multiple-choice questions (three dimensions, for two points in time and four scenarios). With the fatigue factor in mind, the intention was to ensure that panellists completed each round in no more than 30 minutes.

Since candidates had to grasp in a limited amount of time months worth of research, a short summary with the previous work was attached with the link to the survey in the e-mails. This included the purpose of the research, the Delphi, and a short explanation of the previous steps used as input for the Delphi (PI port framework and contextual scenarios).

3.4. Evaluation of PI evolution levels, feedback and interim analysis

During the Delphi rounds, panellists had to assess, for each contextual scenario, the evolution level that each PI dimension would reach on a categorical five-point scale, both for the years 2030 and 2040. Moreover, considering the opportunity to gather knowledge on the topic from experts located geographically apart, they were given the chance to provide feedback, at the end of each round, on the different steps of the Delphi approach proposed in this paper. This included the adequacy to include the years 2030 and 2040, asked as a yes/no question, as well as an open question regarding the proposed PI port framework (named as ”PI port conceptualization” through the survey) at the end of the first round. The detail of the contextual scenarios and the Delphi approach in general were in turn subject to feedback at the end of the second round.

For simplification purposes, experts were not asked to provide a written justification of their selections in the PI categorical levels. Also, for anonymity reasons, panellist did not have to provide their personal and professional information, and therefore all their answers were considered equally. Moreover, because of the limitations of the tool, each expert could not be reminded individually, during the second round, about their previous personal answers. They were alternatively presented with the group response for each question during the second round.

Instead of allowing panellists to select intermediate evolution levels, which would have added complexity and fatigue to the Delphi, each categorical level was assigned a quantitative value after the study, from 1 (Current State) to 5 (Level 4). This was done with the purpose to avoid falling into the discrete and rigid "generations" approach from the UNCTAD [8], by visualizing in-between ratios, while keeping fatigue during the Delphi as low as possible.

Given the categorical results and their equivalent numerical quantification explained above, an interim analysis based on descriptive statistics was performed after both rounds. This included computing the interguartile range (IQR), the mode, mean and standard deviation. The main task was to check for consensus and changes in convergence. Delphi surveys can either seek consensus (see [84]; [47]; [30]; [23]) or allow for dissensus when innovative ideas are preferred [45]. For the case of this paper, there was no room for radical outcomes outside the possibilities to choose from on a five-point scale. Therefore, the aim for consensus was desired in this paper. As consensus criterion, an double step rule was applied. Those with IQR ≤ 1 [19] would be further considered by assessing their percentage of votes at the mode (p[mode]). Consensus would be reached if and only if the previous was met and p[mode] ≥ 50. This rule ensured that more than half of the votes fell within one category (mode), avoiding risk of consensus around two or more points [30], and the breadth of opinions between the 25 percentile and 75 percentile fell next to it.

3.5. Scenario development and recommendations for maritime ports

The PI scenarios were developed from the resulting statistics of the Delphi questionnaire. For each question, the evolution level of each PI dimension reached was chosen to be at the mode, where the highest percentages of votes fell. The level of port connectivity was in turn defined, following the logic behind the PI port framework, as the minimum level of the three PI layers, for each scenario. Since each dimension entailed two points in time, the mode for both years would allow to visualize an evolution path of port connectivity from the current state (assumed to be 2020) until the year 2040. Because of its simplicity, the risk of overlap in the evolution path for more than one PI scenario could be relevant. To avoid it, the mean-based evolution path was also considered, and allowed for interpretation between categorical levels. A major drawback was that the use of ratios were not reflecting the true opinion of experts, since they could only provide a categorical selection on a five-point scale.

To derive recommendations for maritime ports, it was assumed that the goal of port authorities is to maximize the level of port connectivity from the PI port framework for the projected years. They were formulated on the basis of general patterns spotted from the four PI scenarios, considering the current state of each of the dimensions.

4. Results

4.1. Results of Delphi questionnaire

Out of the 78 suitable candidates, 24 answered the first round and 20 answered the second round. On average, it took around 14,5 minutes to complete each of them, which was lower than the 30-minute threshold aimed for. Table 1 summarizes the relevant Delphi statistics, and illustrates how consensus develops between both rounds. The values of IQR and p[mode] are in parenthesis whenever they do not reach the limits established by the proposed consensus criteria. This is the case for 16 out of 24 questions in the first round. Breaking these down, 6 belonged to the governance dimension, while the remaining 10 were equally distributed among the other two layers.

The mode remained at the same category between both rounds nearly for all questions, with the exception of question 13, where the mode initially fell on two categories, and question 20. Also, in all cases, p[mode] increased in the second round, suggesting, together with the previous, that group answers were somewhat consistent with respect to the first round. In line with the common fundamental rational of the Delphi method, convergence generally increased in the second round, with all questions meeting the consensus criteria adopted in this paper (IQR ≤ 1 and p[mode] ≥ 50). The standard deviation, as another indicator of convergence, decreased in all 16 questions where consensus was not initially reached. The largest increase in convergence was in question 5, with a reduction in standard deviation of 48,4%. Increments in standard deviations, or decreases in convergence, albeit small (no more than 9,5% from question 4) occurred in the year 2040 only, which was the case for the three PI dimensions. 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 [34].

Table 1: Delphi statistics: illustration of consensus among experts between both rounds.

Questions	Round 1 (n = 24) ART: 14,36 min					Round 2 (n = 20) ART: 14,33 min						
	IQR	p[mode]	mode	Mean	SD	IQR	p[mode]	mode	Mean	SD	$\Delta Mean$	ΔSD
Scenario 1												
1 Governance (2030)	0	58,3%	L2	2,87	0,88	1	60,0%	L2	2,8	0,60	-2,6%	-31,9%
2 Governance (2040)	0,25	58,3%	L3	4	0,82	0,25	65,0%	L3	3,75	0,83	-6,3%	1,6%
3 Operational (2030)	0,25	66,7%	L2	2,75	0,72	0	65,0%	L2	3,05	0,59	10,9%	-18,3%
4 Operational (2040)	0	66,7%	L3	4,04	0,68	0	75,0%	L3	3,95	0,74	-2,3%	9,5%
5 Digital (2030)	1	(45,8%)	L2	3,04	0,89	1	70,0%	L2	3,33	0,46	8,5%	-48,4%
6 Digital (2040)	1	54,2%	L4	4,33	0,85	1	55,5%	L4	4,35	0,91	0,4%	7,0%
Scenario 2												
7 Governance (2030)	(1,25)	(41,7%)	L1	2,12	0,83	0,5	50,0%	L1	2	0,71	-5,9%	-15,0%
8 Governance (2040)	(2)	(41,7%)	L2	2,95	0,84	1	55,0%	L2	2,65	0,79	-10,4%	-5,8%
9 Operational (2030)	1	54,2%	L2	2,75	0,88	0	70,0%	L2	2,65	0,57	-3,6%	-34,8%
10 Operational (2040)	1	(37,5%)	L3	3,70	0,89	1	55,0%	L3	3,45	0,67	-7,0%	-24,7%
11 Digital (2030)	1	54,1%	L2	2,75	0,88	0	80,0%	L2	3	0,45	9,1%	-49,1%
12 Digital (2040)	1	(45,8%)	L3	3,54	0,91	1	65,0%	L3	3,6	0,86	1,6%	-5,7%
Scenario 3												
13 Governance (2030)	(2)	(37,5%)	CS/L2	2	0,87	1	55,0%	L1	1,9	0,77	-5,0%	-11,3%
14 Governance (2040)	(2)	(37,5%)	L2	2,87	0,93	1	60,0%	L2	2,5	0,67	-13,0%	-27,6%
15 Operational (2030)	1	(41,7%)	L2	2,46	0,82	1	55,0%	L2	2,55	0,74	3,7%	-9,3%
16 Operational (2040)	1	(45,8%)	L2	3,33	0,75	1	55,0%	L2	3	0,77	-10,0%	3,9%
17 Digital (2030)	1	(41,7%)	L2	2,66	0,85	0	75,0%	L2	3	0,63	12,5%	-25,6%
18 Digital (2040)	1	66,7%	L3	3,70	0,61	1	70,0%	L3	3,6	0,66	-2,9%	8,6%
Scenario 4												
19 Governance (2030)	(2)	37,5%	CS	1,91	0,81	1	55,0%	CS	1,6	0,80	-16,5%	-1,5%
20 Governance (2040)	1	(45,8%)	L2	2,5	0,82	1	60,0%	L1	2,2	0,60	-12,0%	-26,5%
21 Operational (2030)	1	(37,5%)	L1	2,29	0,89	1	50,0%	L1	2,2	0,68	-4,0%	-23,7%
22 Operational (2040)	(1,25)	41,7%	L2	3,08	0,91	1	60,0%	L2	2,75	0,70	-10,8%	-23,2%
23 Digital (2030)	1	(41,7%)	L1	2,16	0,75	1	55,0%	L1	2,25	0,62	3,8%	-16,5%
24 Digital (2040)	1	(41,7%)	L2	3,08	0,91	0,5	50,0%	L2	3	0,71	-2,7%	-22,2%

Level	Current State (CS)	Level 1 (L1)	Level 2 (L2)	Level 3 (L3)	Level 4 (L4)
Eq. value	1	2	3	4	5

n: number of respondents SD: Standard Deviation
ART: Average Response Time IQR: Interquartile Range

4.2. Feedback from panel members

There was general agreement on the adequacy to include the years 2030 and 2040 in the Delphi, with 95,3% voting ”yes”. Those few who disagreed referred mainly to the difficulty to visualize an evolution path. Regarding the contextual scenarios provided as input for the Delphi, 75% agreed that they were detailed enough. Those who disagreed mainly referred to the inter-dependencies between the two driving forces, and the difficulty to include the full breadth of uncertainty in a limited number of scenarios. These were already acknowledged by the researchers prior to the panel rounds. Regarding the Delphi study itself, some experts missed an explanation of the categorical selections from other panel members. The researchers were already aware of this shortcoming from the chosen online tool.

Lastly, 45% of the panel members gave feedback on the proposed PI port framework, with comments focusing mainly on three levels. First of all, the framework fixed the ordering of the cells, whereas some experts suggested that ”sometimes it is easier to reach Level 2 (connect terminals) than Level 1 (integrate supply chains)”. Likewise, within the *operational dimension*, more than one expert shared the idea that ”cross-docking and reshuffling or operations might occur earlier than true 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, experts suggested the need for a ”prioritization scheme” among the three dimensions. Thirdly, a few experts argued that the framework itself was incomplete. Some referred to the lack of ”data perspective”, which proved that, since this element was indeed taken into account of the researchers during the characterisation, the summary provided to experts at the beginning of the first round was oversimplified. Content wise, other experts suggested that ”further evolution levels between Level 3 and Level 4 could be useful”.

A final expert check was not conducted to ensure compliance of the categorical results with quality criteria. This could have indeed been needed given the feedback provided by the experts. Yet, considering the time to complete the entire study, the low

Table 2: Summary of evolution levels of the PI dimensions and the port connectivity for all PI scenarios, considering ratios (mean) and categories (mode) respectively.

Criteria		μ (mean)				Mode			
Dimension		Gov_i^T	Op_i^T	Dig_i^T	$PI_{port,i}^T$	Gov_i^T	Op_i^T	Dig_i^T	$PI_{port,i}^T$
PI scenario 1	2030	2,80	3,05	3,30	**2,80**	3 (L2)	3 (L2)	3 (L2)	**3 (L2)**
	2040	3,75	3,95	4,35	**3,75**	4 (L3)	4 (L3)	5 (L4)	**4 (L3)**
PI scenario 2	2030	2,00	2,65	3,00	**2,00**	2 (L1)	3 (L2)	3 (L2)	**2 (L1)**
	2040	2,65	3,65	3,60	**2,65**	3 (L2)	4 (L3)	4 (L3)	**3 (L2)**
PI scenario 3	2030	1,90	2,55	3,00	**1,90**	2 (L1)	3 (L2)	3 (L2)	**2 (L1)**
	2040	2,50	3,00	3,60	**2,50**	3 (L2)	3 (L2)	4 (L3)	**3 (L2)**
PI scenario 4	2030	1,60	2,20	2,25	**1,60**	1 (CS)	2 (L1)	2 (L1)	**1 (CS)**
	2040	2,20	2,75	3,00	**2,20**	2 (L1)	3 (L2)	3 (L2)	**2 (L1)**

fatigue represented by a high response rate, and the group consistency and consensus reached in all categorical questions after both rounds, the results of the Delphi study were taken as valid to develop the PI scenarios.

4.3. PI scenarios

From the Delphi statistics, the PI scenarios were outlined. The evolution levels that the three PI dimensions reach both for year 2030 and 2040 are summarized in Table 2. Gov_i^T, Op_i^T and Dig_i^T represent the level that the governance dimension, the operational dimension and the digital dimension reach respectively at year T for PI scenario i. Numbers in the left column represent the mean value, from 1 (Current State) to 5 (Level 4), while the right column represent the mode. Looking into the mean, evolution levels reached higher in PI scenario 1, with PI scenario 4 having the lowest evolution levels and PI scenarios 2 and 3 laying similarly in between. Likewise, when zooming into the three dimensions, and for all PI scenarios, the digital layer evolved the furthest, the governance reached the lowest levels and the operational fell in between, suggesting a hierarchical order in the proposed characterisation of the PI. Following the minimization rule explained in Section 3.4, the level of port connectivity ($PI_{port,i}^T$) has been computed based on the mean and the mode for each PI scenario.

The evolution path of port connectivity was visualized by joining the values of 2020 (assumed to be the current state) with the years 2030 and 2040. The results for all PI scenarios are plotted in Figure 4, with continuous lines representing the mean and dashed lines representing the mode. Categorical levels are represented in the left hand side of the graph, while their equivalent quantitative values are reflected in the right hand side. The following paragraphs reflect on the different PI scenarios. Albeit having different contextual futures, PI scenarios 2 and 3 are discussed together given their similarities in their evolution paths.

4.3.1. PI scenario 1

The first contextual scenario was dominated by a favorable global institutional integration, where the rise of democracies had expanded to developing countries by 2040. In line with this, major power blocks such as the EU had been able to set up regulatory frameworks that could quickly adapt to market changes, leading to significant technological adoptions and eventually opening room for new cooperative business models. This optimistic contextual environment resulted, through the Delphi study, in the fastest evolution levels of the PI dimensions. Translating to the evolution path of port connectivity, the mode reaches Level 2 in the year 2030, which means achieving the so-called ”Physical Intranet” of the entire port community from the PI port framework presented in Figure 2. This means that same-segment terminals (i.e. ECT or APM Terminals for the case of the port of Rotterdam) are open horizontally within the port and are also intensely connected within the three PI dimensions. Moreover, governing bodies, as well as inbound/outbound modes within the port are also intensely connected. For the year 2040 the mode achieves 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 range if the port of Rotterdam is considered as reference. This could be seen as a form of ”Physical Internet” at a regional (European) level.

The mean suggests a slightly lower evolution, with the ”Physical Intranet” still under adoption for the year 2030, but highly advanced. This could translate to some stakeholders, from operating companies to governing bodies such as customs or the port authority itself, still taking measures to become part of the intra-port connectivity. Similarly, for the year 2040, few ports are still to join the regional PI.

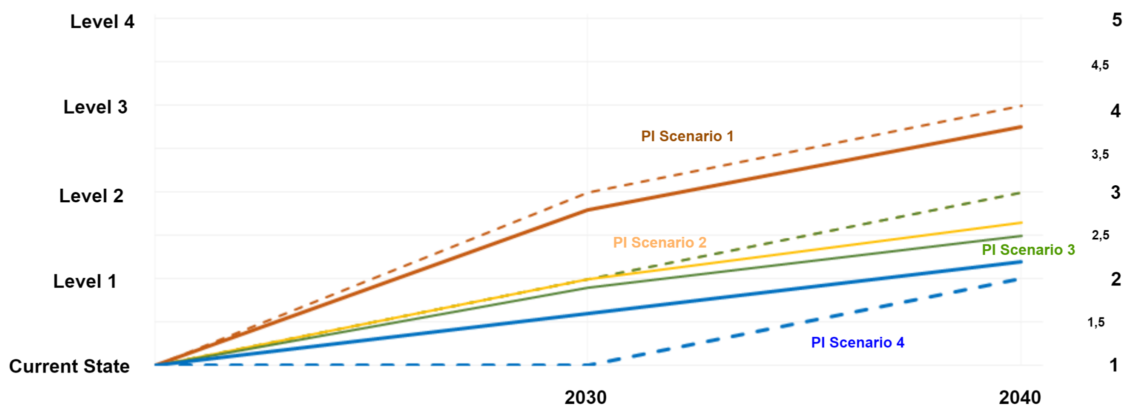

Figure 4: Evolution path of port connectivity for each PI scenario. Mean and mode in continuous and dashed lines, respectively.

4.3.2. PI scenario 4

On the opposite end laid contextual scenario 4, which involved a challenging global setting of high protectionism between major power blocks and slow regulatory frameworks lagging behind market developments. Translating to the development path of port connectivity for PI scenario 4, the mode 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.

4.3.3. PI scenario 2 & 3

Both contextual scenarios 2 and 3 had opposing combination of driving forces. The former was dominated by a favorable globalization context, yet with slow regulatory frameworks lagging behind market developments that would hinder the adoption of new technologies that could ease cooperative models. The third scenario was in turn marked by a highly protectionist environment at the global level, while regional blocks such as the EU had been able to set up regulatory frameworks that could quickly adapt to market changes.

The resulting PI scenarios 2 and 3 laid in between the two opposing PI scenario 1 and PI scenario 4, and evolved in similar evolution paths. In fact, the mode for both PI scenarios overlap completely during the entire time period considered, evolving to Level 1 and Level 2 for the years 2030 and 2040 respectively. This translates to a situation in which 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 scenario 2 evolves slightly faster throughout the entire period than PI scenario 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.

4.3.4. Conclusions from the PI scenarios and recommendations for maritime ports

On the basis of the results, several conclusions could be drawn. First, all PI scenarios confirmed that the Governance dimension would lag behind in terms of development. By adopting the minimization rule from the PI port framework, this layer seems to be the most critical out of the three PI dimensions. Secondly, from the resulting PI scenario 2 and PI scenario 3, it seems that panellists, on average, penalized more an environment of high protectionism (contextual scenario 3) than a future with slow regulatory frameworks lagging behind 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 nodes of freight transport networks is achieved at the regional (European) context at most, equivalent to Level 3. Level 4, considered as the ultimate stage and full global roll-out of the PI, according to its formal definition [52] is never reached in any scenario. If different rules were considered to derive the evolution path of port connectivity, such as a compensation criteria between the three dimensions (i.e. average of the three), global hub hyperconnectivity would still not be reached. Only by using a maximization rule, with the digital dimension as the forerunner, would port connectivity reach close to the latest stage in terms of the mean for PI scenario 1. Yet, the realism of this last criteria should however be subject to debate within the PI community.

4.3.5. Recommendations for maritime ports

Regarding the implications for maritime ports, their aim should be to propose a roadmap that maximizes the slowest evolving of the three dimensions. This means increasing the focus on the governance dimension, which entails several stakeholders working together. Particularizing to the port of Rotterdam as the problem owner of this research, the port authority could play an active advisory role by evaluating and monitoring the implementation of new regulations and harmonized rules, such as the upcoming Rotterdam Rules, in the Netherlands and neighboring countries. Keeping stakeholders informed could allow a parallel and joint implementation among countries. Another example could be the Consortia Block Exemption Regulation (CBER). The port authority could either promote its extension in 2020, or bring in other stakeholders (i.e. port authorities and shipping line representatives) to discuss a more flexible version of the current CBER, while still in compliance with Article 101 of the Treaty of the Functioning of the European Union (TFEU).

While the governance dimension seems to be the major bottleneck towards PI ports, the other two dimensions should not be overlooked. As a current forerunner in terms of automation of ports, digitization and data sharing system within port communities, the port of Rotterdam could, again, play an advisory role with other stakeholders, mainly other port authorities. This means sharing knowledge and experiences with other ports where the operational and digital dimensions are lagging behind.

5. Conclusions and further research

The purpose of this paper was to make a first step to address a large literature gap around the futures of the PI and maritime ports. More specifically, one research question guided the research: "what are the scenarios for the development of maritime ports under the Physical Internet?". To answer this question, a two-round Delphi study was conducted to generate a set of scenarios that depicted the evolution path of the port towards a PI Port, as a function of the development of the PI characteristics

Two blocks were used as to construct the questionnaire. First, a framework that depicts the evolution of the main PI characteristics, which influence the development of the port towards a hyperconnected hub, was constructed. 41 publications in the PI, interviews with PI experts of the PI and subsequent brainstorming session were used as qualitative methods to elaborate the bottom-up framework, with the evolution of each dimension spanning on a five-point scale, from Current State to Level 4. Secondly, contextual scenarios were generated through a scenario logic approach. From desk research, the same interviews with experts and brainstorming sessions, 32 contextual factors, which could potentially influence the evolution of the PI characteristics, were identified and clustered into 7 distinct driving forces. Their relevance was assessed according to the uncertainty of their development and the impact they had on the "system". This was considered to be, following the scenario logic approach, the resulting PI port framework from the previous step. Two driving forces were further selected, and the combination in the directions they could take outlined four contextual scenarios.

From these, a two-round Delphi study was conducted. PI experts located geographically apart selected the level of development of each of the PI characteristics, on a five-point categorical scale, for the years 2030 and 2040. These categorical selection were then translated to a set of PI scenarios, as a function of the three PI characteristics, that outlined the evolution of port connectivity.

This paper makes several contributions. Firstly, it identified a range of potential futures of the PI. Secondly, it made a characterisation of the PI in the context of maritime ports as nodes in freight transport networks. This is, to the best of the authors' knowledge, the first attempt to bring both topics together from an evolutionary perspective. Thirdly, the outcome of the PI scenarios from the Delphi study resulted in a starting point for port authorities to consider the influence of the PI in maritime freight transport systems. A quantification of the evolution of the PI in maritime ports could be a next step. Estimating future cargo flows within the context of the PI for each scenario could further help port authorities design appropriate policies, strategies and related infrastructure. From here, identified potential threats and opportunities based on the different PI freight networks depicted per scenario, a roadmap of actions that ensure maritime ports succeeding in their strategic goals under the influence of the PI could be proposed.

There are limitations to the approach taken in this paper which also open room for further research. As already mentioned, the Delphi study fed on two previous step, and therefore any potential shortcomings from these, which was identified by some panellists during the feedback, could have cascaded down to the questionnaire. The framework focuses on a generic port and its hinterland, whereas port literature emphasize on the uniqueness of each port. Some port may lend themselves better to the framework in the "Current State", such as the port of Rotterdam, than others. Besides this potential mismatch, there could be ports evolving in different orderings of the cells, which was fixed for simplification of the Delphi. Regarding the PI characteristics, the proposed dimensions could have described an incomplete image of the novel concept. This is however in line with the current lack of consensus around the PI. Moreover, the framework was constructed assuming independence of the PI characteristics. Nevertheless, the results from the Delphi studies suggest a hierarchical order. With these inter-dependencies, a synergetic effect might be achieved in the resulting port connectivity, suggesting that the PI itself is more than the mere sum of the three PI dimensions individually. This was however not fully reflected in the framework.

Also, the bottom-up approach did not make use of theoretical models available in literature that depict a transition or development of new innovations. Further studies around the PI, which rely on technological innovations, could make use of these theoretical frameworks. Also, a systematic literature review around both the PI and the evolution of maritime ports should be conducted in further research. Complementing the findings with participatory sessions (i.e. workshops or interviews) could reduce the chances to overlook important characteristics and levels of abstraction within both topics while constructing a well-rounded PI port framework.

Regarding the scenario logic approach, an orthogonality check was not conducted around the selected driving forces, and inter-dependencies were visible during the scenario logic approach. Moreover, the resulting contextual scenarios might be limited compared to the wide range possible hypothetical futures. A participatory approach could have opened room for more valid contextual scenarios. Extra Delphi rounds could be used with the sole purpose to develop contextual factors by the experts, identified through a more rigorous approach, in the PI and ports. Consensus would not be strictly necessary, since the intention would be to give the panellists free room to identify future trends. Yet, provided that little convergence is recommended among experts to avoid non-logical or contradictory opinions, two rounds would be needed at least. With the resulting contextual scenarios, a second two-round Delphi could then be used to generate the PI scenarios, as done in this paper. Adopting this approach could nonetheless increase fatigue among panel members. An interesting alternative could be to use dedicated in-person participatory sessions, such as the SENSE workshops or the annual IPIC. This way, experts in the field of PI, a limited community in comparison to other fields, could participate in more engaging sessions, where potential misunderstandings or questions might be solved, while keeping fatigue of multi-day rounds avoided.

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