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Fahim, Patrick B.M.; Rezaei, Jafar; Montreuil, Benoit; Tavasszy, Lorant

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Port performance evaluation and selection in the Physical Internet

Patrick B.M. Fahim [a,*], Jafar Rezaei [a], Benoit Montreuil [b], Lorant Tavasszy [a]

[a] Transport and Logistics Group, Faculty of Technology, Policy and Management, Delft University of Technology, 2628 BX, Delft, The Netherlands
[b] Physical Internet Center, H. Milton Stewart School of Industrial and Systems Engineering, Georgia Institute of Technology, Atlanta, 30332, GA, USA

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ABSTRACT

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

1. Introduction

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

An innovation that is expected to impact the current economic and trading patterns, technologies, legislation, and governance systems, is the Physical Internet (PI). The term PI was for the first time introduced in the field of transport and logistics in 2006 on the front page of The Economist (Markillie, 2006). It proposes physical packages to be moved similar to the manner in which data packages move in the digital internet (DI). Later, the PI has been defined as "an open global logistics system founded on physical, digital and operational interconnectivity through encapsulation, interfaces and protocols" (Montreuil et al., 2013: p. 1). The innovation is considered to be a breakthrough in the fields of material handling, logistics, transportation, and facilities design (Pan et al., 2017). It claims to ultimately help achieve economic, environmental, and social efficiency and sustainability (Montreuil et al., 2013). Despite its promises and studies that have shown interesting results (e.g. Sohrabi and Montreuil, 2011; Ballot et al., 2014; Pan et al., 2015; Sarraj et al., 2014; Venkatadri et al., 2016), an all-encompassing innovation of this magnitude also creates new uncertainties for many stakeholders,

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* Corresponding author.
E-mail addresses: p.b.m.fahim@tudelft.nl (P.B.M. Fahim), j.rezaei@tudelft.nl (J. Rezaei), benoit.montreuil@isye.gatech.edu (B. Montreuil), l.a.tavasszy@tudelft.nl (L. Tavasszy).

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such as ports, by means of new variables that could impact the future use of the freight transport and logistics system. Intelligent agents as autonomous decision-makers (DMs) is such a new variable that could significantly impact the use of the freight transport and logistics system in a future PI situation. While current port users are often represented by shipping lines, logistics service providers (LSPs), and shippers (Rezaei et al., 2019), we are interested in a similar differentiation in DM perspectives but then in the context of the PI. The PI routing protocol will require a different distribution of decisions over actors, where the envisioned intelligent agents will replace current port users as DMs for port performance evaluation and selection.

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

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

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

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

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

The remainder of this paper is structured as follows: Firstly, an overview of the current literature on port selection and the PI will be provided in Section 2. Section 3 presents the methodology. Section 4, firstly, introduces and discusses the conceptual model, and secondly, presents the results and discusses the most relevant interpretations. Section 5 contains a discussion and some policy implications. Section 6 contains the main conclusions of the research and recommendations for future research.

2. Literature review

2.1. The Physical Internet and the role of hubs

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

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

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

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

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

2.2. Port performance evaluation and selection criteria

To measure a country's overall logistics performance, since 2007, every two years, the World Bank publishes the Logistics Performance Index (LPI) (Arvis et al., 2018a). The LPI analyses the comparative performance and competitiveness between more than 150 countries with regard to *efficiency of customs*, *quality of trade- and transport-related infrastructure*, *ease of arranging competitively priced shipments*, *competence and quality of logistics services*, *ability to track and trace shipments*, and *timeliness of shipments* as the fundamental elements in logistics (Arvis et al., 2018a). The Global Competitiveness Index (GCI), at a broader level, assesses and monitors the performance of countries on twelve pillars, which is published by the World Economic Forum (WEF), annually (Schwab, 2019). In turn, these twelve pillars can be organized into four indices as presented in Table 1.

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

Table 1
Global Competitiveness Index with respective pillars (adopted from: Schwab (2019)).

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

Port performance evaluation and selection is the process of evaluating and selecting the most suitable port by a port user, according to its preferences as part of a transport and value chain (decision), and aims to provide industry and business with concreteness in decision-making problems. The maritime transport chain can be defined as a network of ports and port stakeholders that are involved in the movement of freight over sea. Typically, a port user will have the option to select between alternative ports in a particular geographical region. A port user will select a port according to its preferences, which can often be expressed in port performance evaluation and selection criteria and their respective importance. Table 2 provides an overview of current port performance evaluation and selection studies with respective DM perspectives, and criteria. For a more extensive review of the port performance evaluation and selection literature, we refer to Martinez Moya and Feo Valero (2017).

As can be observed from Table 2, factors related to costs, connectivity, location, capacity, reliability, efficiency, transit time, and IT have been most frequently used in port performance evaluation and selection literature, which also show similarities with the LPI. Additionally, various studies show that the different DM perspectives may have divergent preferences (e.g. Yuen et al., 2012; Magala and Sammons, 2015; Nazemzadeh and Vanelslander, 2015; Martinez Moya and Feo Valero, 2017; Rezaei et al., 2019). Consequently, Martinez Moya and Feo Valero (2017) distinguish between Landside parties, i.e. shippers and LSPs, and Seaside parties, i.e. shipping lines, which function as port selection DMs. While shipping lines tend to design their service networks in such a way that they can gain as much as possible from economies of scale and maximize profits (Guy and Urli, 2006), shippers aim to minimize costs (Talley and Ng, 2013), whereas LSPs' main objectives are to maximize profits by means of consolidation while simultaneously providing their clients with optimal value added services (VAS) (Magala and Sammons, 2015). We are interested in a similar differentiation in DM perspectives but then in the context of the PI, where the PI routing protocol will require a different distribution of decisions over actors, i.e. where intelligent PI containers and vessels will replace the current port users as DMs for port selection.

2.3. Future ports

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

Table 2
Summary of port performance evaluation and selection decision-making perspectives, and criteria.

Author(s)	Decision-making perspective	Criteria
Bichou and Gray (2004)	Not specified	Financial, throughput, productivity, economic, others
Malchow and Kanafani (2004)	Not specified	Oceanic distance, inland distance, sailing headway, vessel capacity, probability of last port
Tang et al. (2011)	Shipping line	Number of port calls, draught, trade volume, port cargo traffic (TEUs), ship turnaround time, annual operating hours, port charges, availability of intermodal transports
Yuen et al. (2012)	Shipping line, Shipper, LSP	Shipping line: Costs at port, customs and government regulation, hinterland connection, terminal operator, port location, port facility, shipping services, port information system. Shipper: Port location, hinterland connections, port costs, customs and government regulation, shipping services, port information system, port facility, terminal operator LSP: Port location, hinterland connections, shipping services, customs and government regulation, costs at port, port information system, terminal operator, port facility.
Veldman et al. (2013)	Not specified	Inland transport costs, maritime transport costs, other cost and quality of service aspects, choice of coast line, inland transport cargo balance
Kurt et al. (2015)	Shipping line	Location, Connectivity, port operation and performance, port capacity, investment opportunity and decision in the port facility
Magala and Sammons (2015)	Shipping line, Shipper, LSP	Accessibility, connectivity, efficiency, service quality, level of integration, flexibility, port charges, carbon footprint, transit time, frequency, availability, freight rates, reputation, on-time delivery, reliability
Nazemzadeh and Vanelslander (2015)	Shipping line, Shipper, LSP	Port costs, geographical location, quality of hinterland connections, productivity, capacity, costs, quality of operations, reputation of operator, and port location
Van Dyck and Ismael (2015)	Not specific	Port efficiency and performance, political stability, port costs, port infrastructure, cargo volume and port location
Lee and Lam (2016)	Not specified	Reliability, resilient system, ICT, green port development, port cluster, VAS, port connections, inland connections
Arvis et al. (2018b)	Not specified	Container and transshipment volume, port or terminal productivity, roll-on/roll-off volume and services, hinterland connectivity and economic zones, port governance
Chu et al. (2018)	Not specified	Automated equipment, equipment-control systems, terminal control tower, human-machine interactions, interactions with the port community
Ha et al. (2019)	Not specified	Productivity, lead time, human capital, organisation capital, service reliability, service costs, intermodal transport systems, VAS, IC systems, IC integration practices
Port of Rotterdam (2019)	Not specified	VAS, port-related employment, decarbonisation, public-private investments, connectivity, safety, air quality, global hub function
Rezaei et al. (2019)	Shipping line, Shipper, LSP	Total costs, maritime transit time, inland transit time, frequency of shipping, satisfaction deep sea, first port of call, customs service, frequency inland lines, last port of call, satisfaction terminals, number of inland operators, port reputation, number of terminals
Dong and Franklin (2021)	Shipper	Cost, time, schedule, emissions, capacity

developing its global hub function, industrial cluster, connections between the port, city and region, land and infrastructure, human capital, and innovation ecosystem.

2.4. Literature gaps and expectations

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

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

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

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

3. Methodology

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

Our empirical research approach is built around the MCDA method and is as follows (see Fig. 1):

- Step 1 aims to establish the set of criteria. For this purpose, we conduct a series of 10 semi-structured face-to-face expert interviews. We use the semi-structured format to be able to give the experts some direction, while also allowing them to express their opinions and add to the discussion. We selected the 10 experts based on their experience with ports and/or PI, from academia, applied research institutes, and industry. Appendix A provides a list of the experts with respective functions and affiliations.

- In step 2, a survey among a group of experts is conducted to obtain data as input for the Bayesian BWM. The group comprised 34 experts from academia, applied research institutes, and industry. Appendix B provides a list of the respondents with respective functions and affiliations. These experts are selected based on their academic experience with ports and/or PI, their (scientific) contributions to ports and/or PI, and industry experience. Appendix B presents the list of the experts that participated in the survey.

- In Step 3, since we are dealing with the preferences of a group of experts, we employ the Bayesian BWM. The Bayesian BWM is a pairwise comparison-based MCDA and is specifically designed to obtain the relative priorities, i.e. aggregated final weights, of criteria for a group of DMs all at once (Mohammadi and Rezaei, 2020a). In addition to obtaining the relative priorities, another valuable feature of the Bayesian BWM is that it provides ranking schemes, called credal rankings, which are able to measure the degree to which a group of DMs prefer one criterion over another by means of a confidence level (Mohammadi and Rezaei, 2020b). The group shows to be more certain about the relationship between two criteria if the respective confidence level is high. The comparisons of the criteria with their respective confidence levels are visualized using weighted directed graphs.

4. PI port performance and selection

4.1. Criteria

Table 3 tabulates the set of criteria that have been established by means of executing Step 1 of the Methodology. In order to select the most suitable port, each decision alternative, i.e. port, should be evaluated against the set of criteria. The criteria are grouped into four classes (see Table 4). Transport Chain Quality (TCQ) considers criteria that are not restricted to the port itself, but consider the complete transport chain instead. The Costs class considers the criteria that are directly related to the costs of the transport chain and the costs incurred at the port, while Technology considers criteria at the port that are technology driven. Network Quality of Port (NQP) considers the criteria that contribute to the quality of the port in the network. Most of the criteria are directly linked to the PI literature and can be categorized into one of the eight PI Building Blocks.

4.2. Criteria weights

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

4.2.1. The container perspective

Table 4 presents the classes and criteria with the respective means of the weight distributions in terms of local and global weights. Local weights indicate the weights within the respective class, while global weights indicate the overall weights. It can be directly observed from the table that Costs (0.325) are perceived as the most important class, followed by TCQ (0.305), NQP (0.225), and Technology (0.145). On a criteria level, we can observe that Transport Costs (0.205), Transshipment Costs (0.120), LoS (0.092), NI (0.091), and GL (0.077) are considered most important.

Based on Fig. 2, which shows the credal ranking of the classes from a container perspective, we can conclude that Costs (0.325) is considered the most important class with a full confidence of 1 over NQP (0.225) and Technology (0.145). However, Costs is superior over TCQ (0.305) with merely a confidence level of 0.70, simultaneously indicating that TCQ is superior over Costs with a confidence level of 0.30. Although it has been argued that a confidence level of 0.50 can be used as a threshold value (Mohammadi and Rezaei, 2020a), it does indicate that there is some dissension between the experts' opinions about this particular relationship.

Fig. 3 shows the credal ranking with respective confidence levels of the criteria within the Technology class. It can be observed that ISs (0.065) are considered more important than both AoO (0.041) and Smart (0.040) systems with a full confidence level. However, AoO is considered more important than Smart with a confidence level of 0.57, implying that these criteria are considered almost equally important among the different experts.

All other credal rankings of the criteria from a container perspective

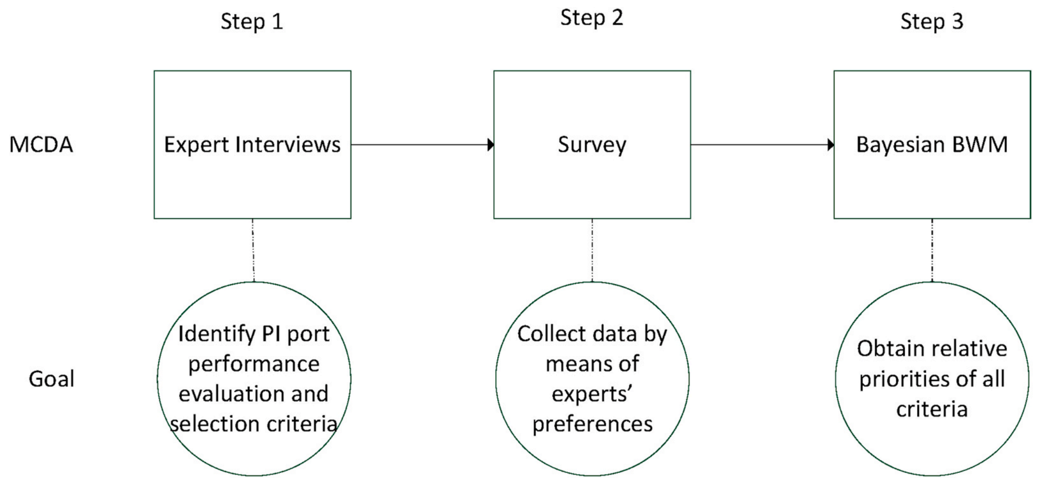


Fig. 1. Research methodology.

Table 3
Port performance evaluation and selection criteria with respective descriptions.

Criterion	Description
A1. Level of Service (LoS)	Factors describing *level of service (LoS)* quality such as transit time (Sarraj et al., 2014; Rezaei et al., 2019), availability of vessel (Ballot et al., 2012), port throughput time (Meller et al., 2012), port and route congestion (Montreuil et al., 2012), and agility, flexibility and responsiveness (Montreuil et al., 2018). These factors are becoming increasingly more important in today's logistics, and are expected to keep doing so in the dynamic environment of the PI, where agility, flexibility, and responsiveness are essential elements of the network (Montreuil et al., 2018).
A2. Reliability	The *reliability* of the transport chain is reflected by the potential risk of complete port and/or vessel disruption, the defect and loss rate, financial stability of port and/or vessel (company) (Rezaei et al., 2014), and the client rating of a particular route with respective ports (Ballot et al., 2014), based on historical and real-time data, and future predictions. Client rating is based on a system that will allow users to assess service providers by means of a PI rating (Ballot et al., 2014).
A3. Physical Port Infrastructure (PPI)	*Physical port infrastructure (PPI)* includes the factors number of terminals (Ballot et al., 2012), available handling capacity (Nazemzadeh and Vanelslander, 2015), and overall efficiency of the PPI (Martínez Moya and Feo Valero, 2017). Whereas LoS reflects the actual state of the operations, the first two factors here are related to the potential overall capacity of the PPI, while the overall efficiency is related to the potential pace in which a container and vessel can move through, i.e. in and out of, a port.
A4. Sustainability	Strengthening the environmental *sustainability* of the global freight transport and logistics system is ultimately one of the goals of the PI (Montreuil et al., 2013). Here, we include port emissions, vessel emissions, nuisances (to the port environment) (Ülengin et al., 2010; Sarraj et al., 2014), social responsibility (Rezaei et al., 2014), and air quality and noise (Caramuta et al., 2018).
A5. Safety & Security (S&S)	*Safety* concerns labour related injuries and casualties caused by both vessel transport and container handling operations at the port (Caramuta et al., 2018). *Security* addresses the traditional issue of theft (Kheybari and Rezaie, 2020) and the increasingly important issue of cybersecurity. The latter is to play a crucial role in the digitally hyperconnected system of the PI.
B. Costs	*Transportation costs* will be dependent on a particular vessel with respective route (Sarraj et al., 2014; Rezaei et al., 2019), while the *transshipment costs (TC)* are variable and relate to the handling and operations charges at a specific port or terminal (Sayareh and Alizmini, 2014) from a container perspective. *Seaport duties (SD)* are fixed costs and directly paid by vessels(' companies) to ports to be able to call at a port and retain their services (Yuen et al., 2012). Here, it must be kept in mind that a vessel will only call at a particular port when a minimal critical number of containers will be (off)loaded at that port. In the PI, this will be done dynamically and during the voyage before reaching a port.
C1. Automation of Operations (AoO)	*Automation* here represents a port's equipment and technology to conduct operations that are critical for the PI, such as (off)loading, handling and reshuffling of PI containers in an automated manner (Montreuil et al., 2015). The capability of handling a Unified Set of Standard Modular PI Containers will be a prerequisite for a port to be able to operate and participate in a fully operational PI network (Montreuil, 2020).
C2. Information Systems (IS)	*Information Systems (IS)* refers to the level of sophistication of ISs, such as Port Community Systems (PCS) to which all port actors are connected (Chu et al., 2018), but also (internal) track-and-tracing systems. Well-functioning PCSs will be able to serve the more multi-party and multi-service nature of PI hubs (Montreuil et al., 2018). Also, seamless integration and interoperability of IS (Ha et al., 2019)), data availability and accessibility, data transparency, data accuracy and quality, and real-time availability of data are included here.
C3. Smart	Becoming an open data-centric smart global network is one of the foundations of the PI. *Smart* represents the manner and degree to which ports and vessels use optimization, heuristics, simulation and machine learning techniques to optimize their communicational and decisional capabilities (Montreuil, 2020). In addition, one of the suggested fundamental transformations for PI hub design is hubs' capabilities to conduct smart dynamic decisions on the container routing and the internal flow orchestration (Montreuil et al., 2018).
D1. Geographical Location (GL)	The *geographical location* of a port is of importance (Kinra, 2015; Nazemzadeh and Vanelslander, 2015). Here, we consider both the inland distance (from origin to port and/or port to inland destination) and the oceanic distance (from port to port) of the route (Magala and Sammons, 2015). In addition, we refer to a port's natural (dis)advantages regarding its location, such as a port's accessibility by (deep-sea) navigable waterways (Rodrigue, 2016), and its draft restrictions (Castelein et al., 2019).
D2. Logistics (LF)/Maintenance Facilities (MF) around Ports	*Logistics facilities (LF)* around ports, such as warehousing, VAS (Lee and Lam, 2016) and customs procedures (Kinra, 2015) are relevant from a container perspective. *Maintenance facilities (MF)* around ports for vessels for repair purposes also contribute to the network quality of ports. PI hubs are to become more multi-party and multi-service (Montreuil et al., 2018).
D3. Network Interconnectivity (NI)	By means of the *network interconnectivity (NI)*, we refer to a port's both maritime and hinterland connectivity (Lee and Lam, 2016), a port's intermodal connections (Tongzon, 2009; Kinra, 2015; Ha et al., 2019), and frequency of shipping at a port (Ballot et al., 2012). Port connectivity represents the number of both foreland and hinterland nodes that a port is connected to (Magala and Sammons, 2015).

have shown to be in full or almost full confidence levels. Hence, the conclusion can be drawn that all other class and criteria weights, shown in Table 4, are determined with full or almost full confidence levels.

4.2.2. *The vessel perspective*

Table 5 presents the classes and criteria with the respective means of the weight distributions in terms of local and global weights. It can be directly observed from the table that also here Costs (0.369) are perceived as the most important class, followed by TCQ (0.264), NQP (0.207) and Technology (0.160). On a criteria level, we can observe that

Table 4
Weights of classes and criteria from a container perspective.

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

Transport Costs (0.213), SD (0.156), GL (0.091), LoS (0.076), and ISs (0.072) are considered most important.

Fig. 4 shows the credal ranking with respective confidence levels of the criteria within the TCQ class. All the confidence levels show to be full or almost full, except from Reliability to PPI with 0.72, which means that there is some more dissension between the experts' opinions about this particular relationship than between others. All other credal rankings of the classes and criteria from a vessel perspective have shown to be in full or almost full confidence levels. Hence, the conclusion can be drawn that all other criteria weights, shown in Table 5, are determined with full or almost full confidence levels.

4.2.3. Comparison

Fig. 5 shows the results from both a container and vessel perspective on class level. At first sight, the results from both perspectives look similar. In both cases, Costs are the most important class, followed by TCQ, NQP and Technology, in that order. The strongest discrepancies between the container and vessel perspective can be found in Costs and TCQ. Costs show to be more dominant from the vessel perspective, while TCQ is considered more important from a container perspective. Weaker relative discrepancies are found in Technology and NQP. Vessels have been found to value Technology more, while containers have a higher preference for NQP.

Table 6 and Fig. 6 show the results from both a container and vessel perspective on a criteria level. At first sight, again, the results from both perspectives look similar. However, the strongest discrepancy can be found in the importance that vessels attribute to SD and containers attribute to TC. Vessels consider SD as more important than containers consider TC. Although these are different criteria, they both measure the costs incurred by means of going to or through a port. Hence, here we could argue that less ports on a particular route is more important to a vessel than to a container. The second strongest discrepancy can be found in NI. This criterion is considered more important from a container perspective than from a vessel perspective. Here, we can argue that experts value the importance of a container having ample intermodal connections and connecting ports in reach to route to their final destination higher than similar traits for vessels, including the importance of consolidation opportunities for a vessel. The third strongest discrepancy can be found in S&S and LoS. S&S is considered more important from a container perspective than from a vessel perspective. Here, it can be argued that it seems plausible that cargo owners are more concerned over the wellbeing of their cargo than the vessels are concerned over the cargo and general safety. Although LoS is also significantly important to the vessel, the higher importance from a container perspective can be explained by the pressure that nowadays rests on suppliers and end-to-end service providers to make sure that their cargo arrives at their customer rapidly and on time. The lowest discrepancies have been found in Smart, LF/MF, Sustainability, and IS.

5. Discussion

Information on the above criteria is of crucial importance to support PAs in their consideration of investment directions and the design of policies to enhance the competitiveness of their ports (Martinez Moya and Feo Valero, 2017; Van der Lugt et al., 2017). In this section, we position our findings in the literature, reflect on the expectations stated in Section 2, and discuss some policy implications for PAs.

Table 7 tabulates the most important criteria from both a container and vessel perspective that we found in our research. We can see that the

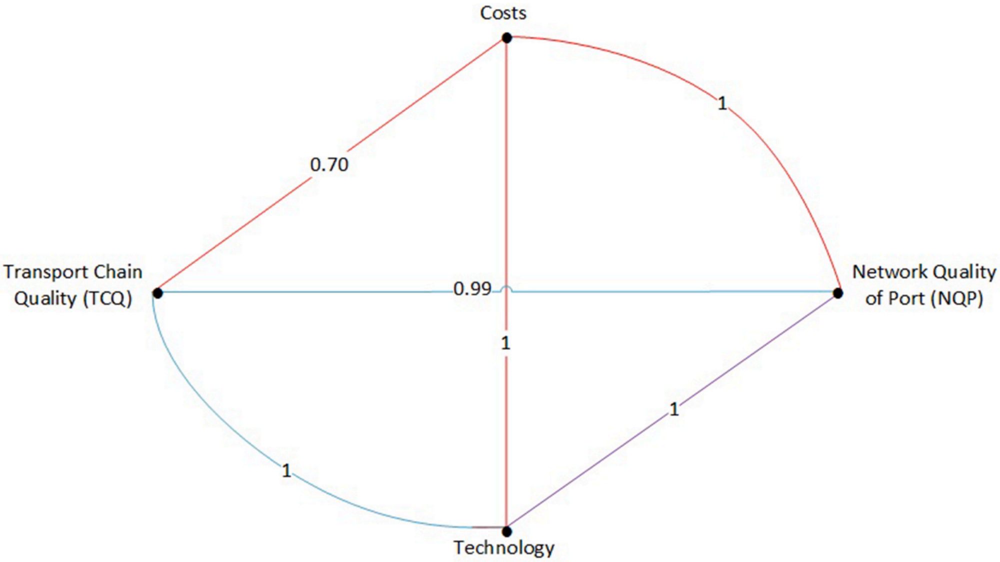


Fig. 2. The credal ranking of classes from a container perspective.

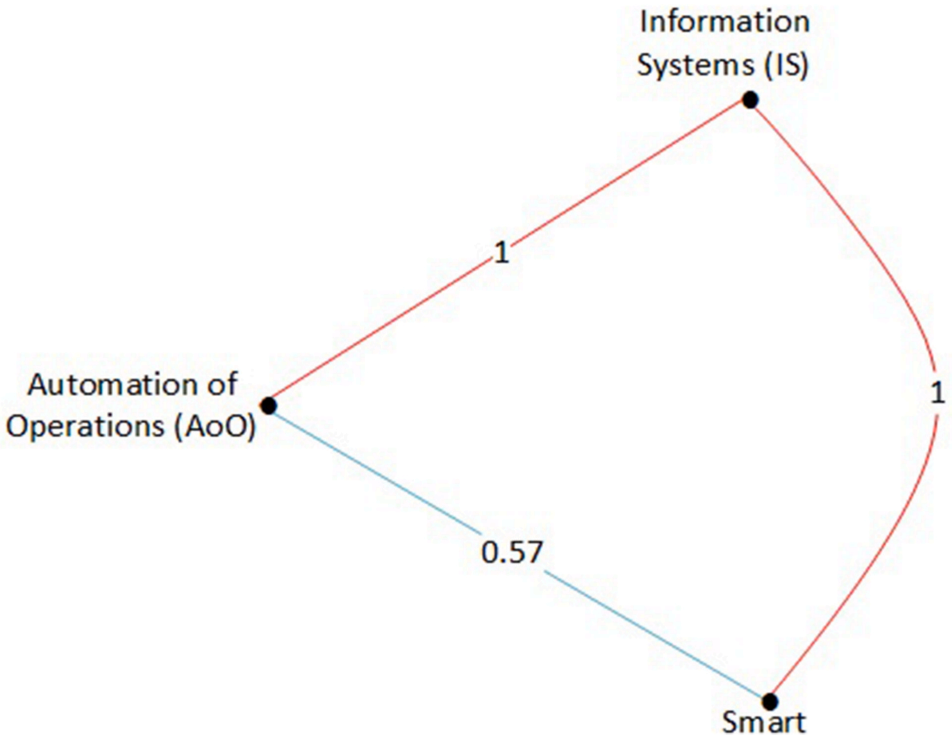


Fig. 3. The credal ranking of Technology criteria from a container perspective.

Table 5
Weights of classes and criteria from a vessel perspective.

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

6 most important criteria, although in a different order of importance, are the same from both perspectives.

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

Overall, the relatively low weights of criteria, such as Sustainability, Smart, AoO, and PPI can perhaps be considered somewhat unexpected since the PI has been described as a system with its core foundations including automation technology and optimized operations to eventually be able to provide a solution to the current environmental unsustainability in freight logistics. However, at the same time, criteria NI, ISs and LoS have been perceived as highly important criteria, which is in line with the principles of the PI and our earlier stated expectations in Section 2. The high importance of NI is in line with the expectation that both containers and vessels are more likely to select a port where the opportunity is greater to catch a vessel that follows a desirable route, and where the opportunity is greater to (un)load a larger number of containers, respectively. The high importance of IS is fully in line with our stated expectation that ports in the PI are required to becoming more active agents in (digital) supply chains, and facilitate and support its community's needs regarding real-time data processing and sharing, and physical and digital hyperconnectivity. The high importance of LoS is, again, fully in line with earlier stated expectations that PI hubs will require to become more efficient, agile, and responsive through real-time dynamic decision making on the container consolidation and internal flow orchestration. Another clear observation is that Costs are perceived as by far the most important criterion, which is in line with the current port selection literature and cannot be considered surprising taking into account the nature of the logistics function and business environment in general.

Reflecting on GCI and LPI, from our results, we can draw similar conclusions as Önsel Ekici et al. (2019) and Kabak et al. (2020). We argue that policymakers, from a port management perspective towards a future PI situation, should focus even more on ICT adoption and innovation, to further increase efficiency of customs, ease of arranging competitively priced shipments, competence and quality of logistics services, and the ability to track and trace shipments, while taking into account commercial pricing strategies in the markets. Simultaneously, PAs could invest in optimizing operations, and improving infrastructure and overall connectivity to ensure quality of trade- and transport-related

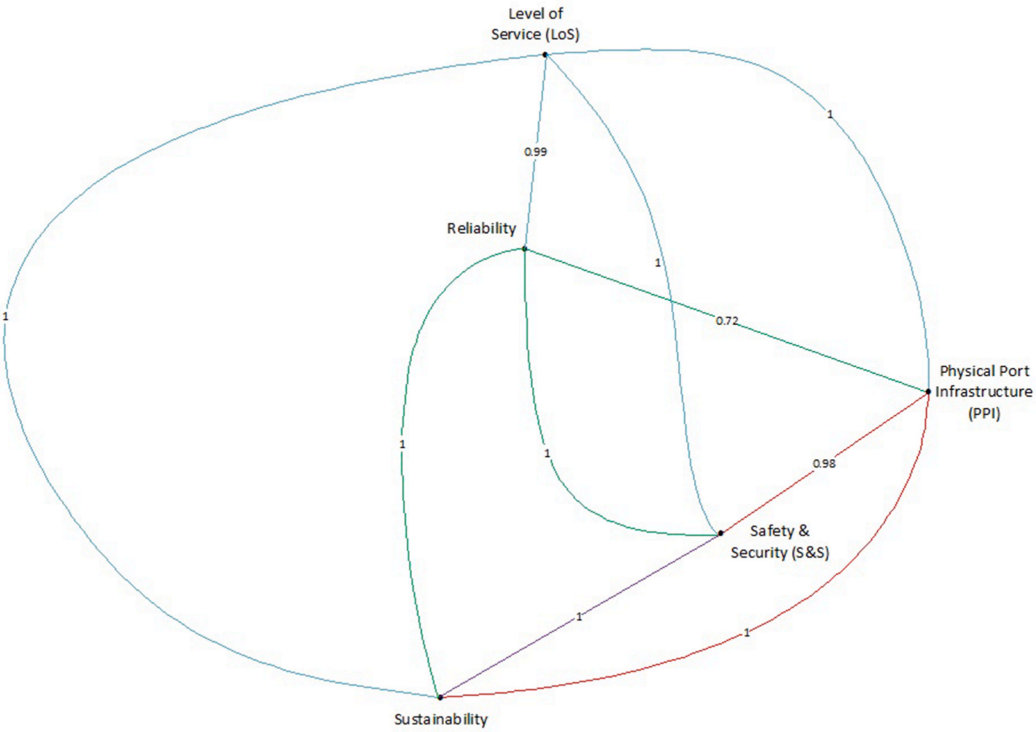
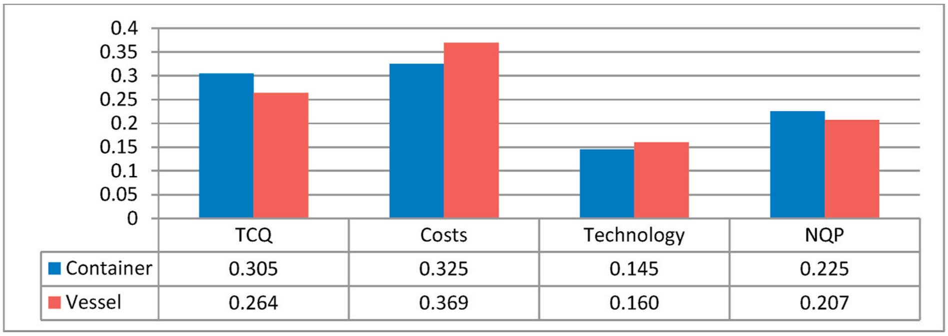


Fig. 4. The credal ranking of TCQ criteria from a vessel perspective.



	TCQ	Costs	Technology	NQP
🟦 Container	0.305	0.325	0.145	0.225
🟥 Vessel	0.264	0.369	0.160	0.207

Fig. 5. Classes' global weights comparison between container and vessel perspective.

Table 6
Criteria's global weights comparison between container and vessel perspective.

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

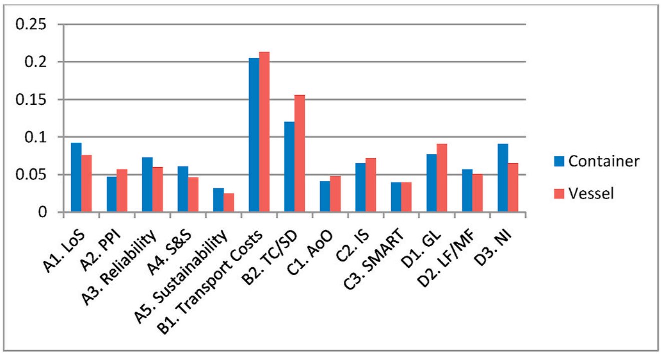


Fig. 6. Criteria's global weights comparison between container and vessel perspective.

Table 7
Most important criteria from a container and vessel perspective.

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

infrastructure, and timeliness of shipments. Regarding human capital, there is a bit of a paradox since one might argue that, one the one hand, blue-collar labour might become obsolete and unnecessary because of automation and intelligence within systems, while simultaneously more complex systems ask for increasingly skilled, competent, and educated labour.

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

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

6. Conclusions and future research

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

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

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

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

Author statement

The authors hope that this first stage in the modelling of intelligent agents' performance preferences in the PI will inspire other researchers to further contribute to this crucial topic of development. Additionally, we would like to sincerely thank the journal reviewers and editors for their invaluable comments to get to the result of this paper. Furthermore, we would like to sincerely thank the interviewees and respondents for their invaluable research input.

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Appendix A. List of Expert Interviewees

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

Appendix B. List of BWM Survey Respondents

Function	Affiliation
Senior advisor	ALICE (Alliance for Logistics Innovation through Collaboration in Europe)
CEO	Consulting company
CEO	Consulting company
Professor	Delft University of Technology
Professor	Delft University of Technology
Researcher	Delft University of Technology
Senior Director	European Inland Waterways Platform
Strategic Initiatives	Fraunhofer
Professor	Georgia Institute of Technology
Researcher	Georgia Institute of Technology
Researcher	Georgia Institute of Technology
Researcher	Georgia Institute of Technology
Researcher	Georgia Institute of Technology
Researcher	Georgia Institute of Technology
Researcher	Georgia Institute of Technology
Researcher	Georgia Institute of Technology
Researcher	Georgia Institute of Technology
Business Consultant	Globally leading LSP
Transportation Network Planning Manager	Globally leading LSP
Senior Manager Transport & Logistics	GS1
Supply Chain Manager	Heineken
Professor	Kedge Business School
Professor	Kuehne Logistics University
Professor	Kuehne Logistics University
Head of Innovation	Port of Algeciras
Innovation Manager	Port of Barcelona
Head of Strategy & Analytics	Port of Rotterdam
Strategist	Port of Rotterdam
Research Fellow	Procter & Gamble
Director	Transport Systems Catapult
Professor	University of Groningen
Professor	University of Groningen
Researcher	University of Groningen
Professor	University of Melbourne

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