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

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ABSTRACT

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

1. Introduction

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

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

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

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

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

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

The rest of the paper is built up as follows. An overview of the relevant port, PI, and IA literature is provided in Section 2. Section 3 introduces the methodology. Section 4 presents a real-world case, which is followed by conceptual design of the IA in Section 5. Section 6 provides a discussion, while Section 7 presents the conclusions of our work and recommendations for future research.

2. Literature review

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

2.1. Maritime port evolution and developments

In the maritime port logistics literature, the evolutionary path of ports has been described through several generations (Lee and Lam, 2016). Ports, over time, have evolved from first generation ports (1GPs), which merely served as gateways between land and sea, and are now moving into fifth generation ports (5GPs), which are considered highly complex and dynamic multi-actor systems with advanced (information) technologies and a wide range of (value-added) services, in addition to the traditional ones. Lee and Lam (2016) emphasize the key roles of new information technology (IT) in the most modern 5GPs, notably contrasting their IT features versus those of fourth-generation ports (4GPs). Essentially, IT in 4GPs focuses on providing cargo clearance and T&T services on container level, whereas IT in 5GPs goes one step further by offering its users a single window (SW) by means of Port Community Systems (PCSs) for information exchange about T&T of not only maritime containers but also its contents (on a shipment level), delivery information, and performance measurement (Lee and Lam, 2016). Another more recently developed concept that explains current and future practices, and is closely linked with PCSs, is Port Collaborative Decision-Making (PortCDM). By making the foreland operations as predictable and real-time as possible, PortCDM makes not only processes in one port more efficient, but will also contribute to an increase in the efficiencies of other ports and vessels (Lind et al., 2020).

A distinction can be made between internal T&T systems inside a particular (local) logistics system, such as a port, and external T&T systems across the supply chain. In 5GPs, PCSs fulfil the function of, among others, T&T across the supply chain (EPCSA, 2011a). A PCS can be defined as a neutral and open electronic platform, enabling intelligent and secure exchange of information between public and private actors to improve the competitiveness of port communities (EPCSA, 2011b). PCSs aim to contribute to optimizing, managing, and automating port and logistics processes through a single submission of data and connecting supply chains (IPCSA, 2018). Globally, various PCSs with a range of functionalities have emerged over the years (e.g. Dakosy in Germany, Logink in China, Maqta in United Arab Emirates, Portbase in the Netherlands). In addition, initiatives are being taken to expand the knowledge capacity and enhance usability of these systems among its actors, often led by the European and International PCS Associations (EPCSA and IPCSA), and United Nations. In line with the objective of the PI becoming an open global freight transport and logistics system through physical, digital and operational hyperconnectivity (Montreuil, 2011), future

PCSs aim to support T&T capabilities and interoperability across supply chains (UNESCAP, 2018). However, the PI has not been considered in the PCS literature whatsoever. The requirements of the PI concerning T&T capabilities of a port should be known to be able to develop PCSs in line with the 5GP vision.

2.2. Physical Internet (PI)

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

2.2.1. Encapsulation

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

2.2.2. Interfaces

In order to provide transport and logistics services, the PI system needs to consider both *physical (operational) interfaces* as well as *information and communication (I&C) interfaces*, as emphasized in Montreuil et al. (2012) and synthesized in Table 1. The interactions and the exchanging data sources between the two interfaces provide the new context for increasing the visibility in transport chains. While the high-level interfaces focus on logistics services, the low-level interfaces focus on the PI containers at which the information is carried.

2.2.3. Protocols

The PI enables the interconnected exploitation of logistics networks through cooperative protocols agreed upon and exploited by the variety of actors in the logistics chains. PI protocols not only ensure the integration of logistics entities but also their performance, resilience, and reliability in PI networks (Montreuil, 2011). Standardized PI routing protocols will facilitate dynamic routing of PI containers across multiple modes of transport in the PI network. To connect logistics networks and services by means of protocols in the PI, Montreuil et al. (2012) proposed the Open Logistics Interconnection (OLI) model as the PI's equivalent to the Digital Internet's Open Systems Interconnection (OSI) model. Fig. 1 depicts the OLI model with its seven layers and respective protocols. The layered protocols of the OLI model provide a framework for exploiting physical, digital, financial, human, and organizational means of the PI (Ballot et al., 2014). On each layer, an instance provides services to an instance on a higher layer, while receiving services from an instance on a lower layer. Simultaneously, instances on the same layer can also provide and receive services to and from each other. Note that, from the OLI perspective, a T&T functionality within a port will primarily conduct the operations within L1, L2, and L3, while supporting routing and shipment decisions at L4 and L5. A port, as a hub, allows for routing decisions, the rearrangement of products by means of PI containers, and their assignment to service classes. In line with the OLI, the to be designed IA considers how data is transmitted between different layers.

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

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

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

2.3. Information Architectures (IA)

More recently, with the introduction of IoT and blockchain as enablers for a wide range of applications in logistics and supply chain management (Galati and Bigliardi, 2019), various IAs have been proposed with specific applications (Yaqoob et al., 2017). Bisogno et al. (2015) created an integrated information flows model for PCSs to improve intelligent logistics services by means of adopting a case study approach, investigating the Port of Salerno. Li et al. (2016) argued that in current logistics, there is a lack of devices that can effectively provide visibility on real-time in-transit infor-

Table 1
Types and Levels of Interfaces.

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

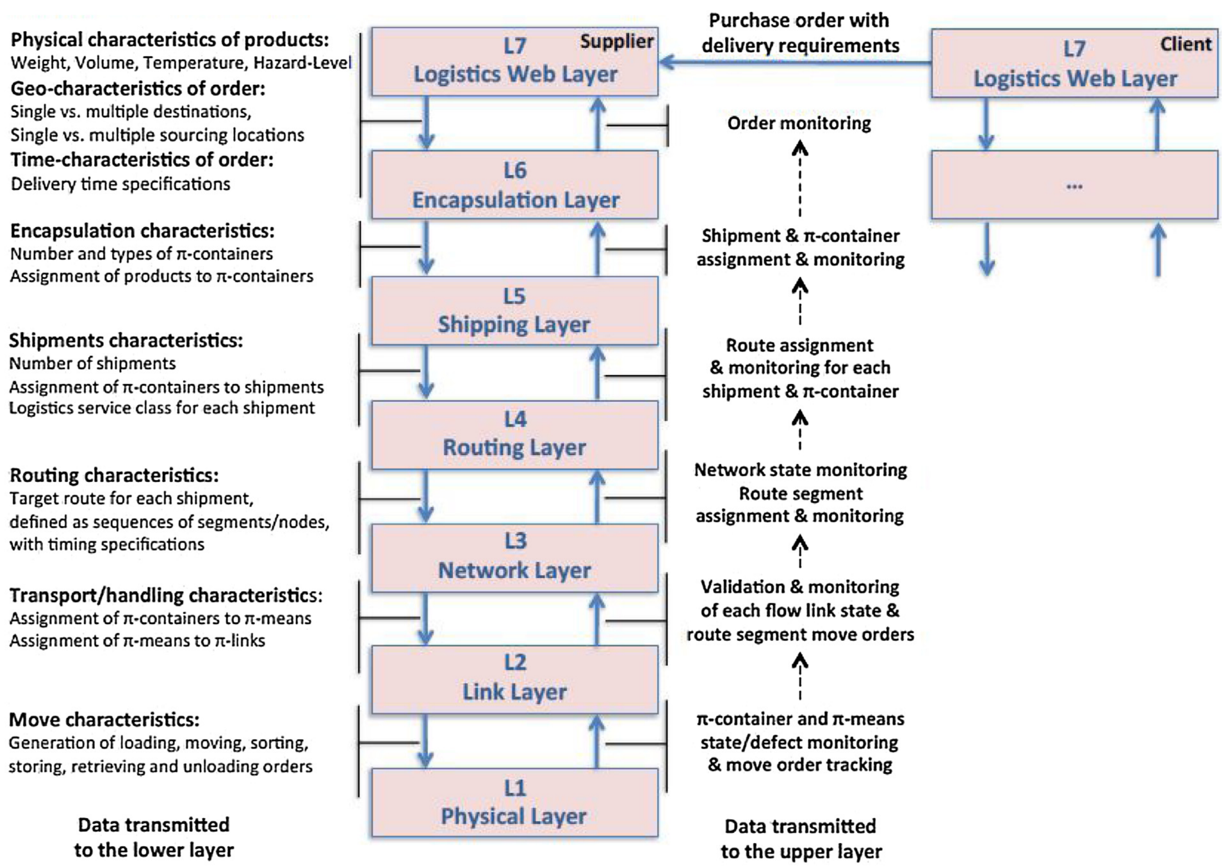

Fig. 1. The seven-layer OLI model with respective inter-layer service description (adopted from: Montreuil et al., 2012).

mation of container freight. Hence, they constructed a T&T device architecture based on IoT technology in combination with a multi-sensor device to provide real-time in-transit visibility. Tian (2016) studied the utilization of radio frequency identification (RFID) and blockchain technology in building an agri-food supply chain traceability system. They developed a system that realizes traceability with trusted information, which would effectively guarantee the food safety by gathering, transferring, and sharing data in production, processing, warehousing and distribution. Raap et al. (2016) proposed an architecture for an integration platform that supports the automated collection of real-time container tracking data for the purpose of more efficient planning by logistics service providers (LSPs). Byun et al. (2017) developed a system architecture that contributes to their graph-oriented persistence approach to achieve efficient and privacy-enhanced object traceability based on unified and linked electronic product code information services. Betti et al. (2019) and Hasan et al. (2020) both focused on exploiting blockchain within a PI context. While Betti et al. (2019) proposed smart contracts to improve PI trustability and cybersecurity, Hasan et al. (2020) presented two permissioned blockchain architectures that provide decentralization, privacy, trust, immutability, and transparency in PI networks. Also in the food supply chain area, Mondal et al. (2019) proposed a blockchain inspired IoT architecture for the purpose of enhancing transparency. The architecture was based on the integration of RFID-based sensor at a physical layer, while applying blockchain technology at the cyber layer. Van Geest et al. (2021) presented a generic business process model for smart warehouses, while simultaneously modelling its reference architecture.

The IS literature has recently evolved in terms of providing RAMs for innovative IA designs. Similar to the PI, Industry 4.0 has the potential to impact entire industries by transforming the way goods are designed, manufactured, delivered, and paid (Hofmann and Rüsch, 2017). They both integrate cyber-physical systems in the production and logistics domain and the use of web-based services in industrial processes (Galati and Bigliardi, 2019). Lasi et al. (2014) and Boyes et al. (2018) argue similarly that Industry 4.0 demands architectures which support its implementation in different areas, from the design of products to the distribution with the participation of actors connected by a collaborative network in a distributed environment. Weyrich and Ebert (2015) propose five RAMs that are suitable for IoT applications: RAMI 4.0; Industrial Internet Reference Architecture (IIRA); IoT-Architecture; Standard for an Architectural Framework for IoT; and Arrowhead Framework. Although each of the RAMs has its merits, RAMI 4.0 provides the extended ability to focus on multiple system layers, while considering hierarchical levels, life cycles and value streams (Pisching et al., 2018). In addition, RAMI 4.0 allows for the description and implementation of highly flexible concepts in a standardized way, whereas other RAMs have a strong focus on specific use cases (Adolphs et al., 2015). In essence, RAMI 4.0 provides a “basic reference architecture” for Industry 4.0 (Bangemann et al., 2016), and hence, many major companies and institutions in various industries use RAMI 4.0 (Weyrich and Ebert, 2015).

2.4. Literature gaps and contribution

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

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

3. Methodology

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

The focus of the design problem is summarized in Fig. 2. The PI has a well elaborated system architecture, the OLI model, relating to the activities, decisions and components underlying the demand for, and delivery of, freight transport services. This domain model of the PI also specifies an information need. The IA for the system to satisfy this need can be designed based on a RAM, by defining the components of the model in the domain context. Together, these sketch the design problem, where our focus lies on the design of the PI Port T&T IA.

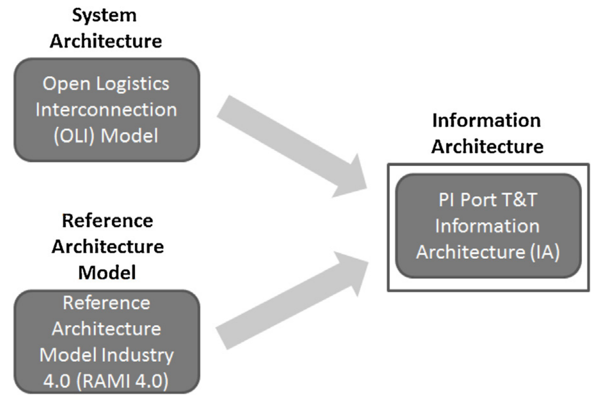

Fig. 2. Design Focus.

3.1. Design Science Research (DSR)

Research within the field of ISs is considered to be a discipline that combines technical research on IT, the application and business uses of IT, as well as its natural, social, and behavioural scientific dimensions (Gregor and Hevner, 2013). According to Weber (2018), within the IS research discipline, traditionally there are two types of research: (1) classical research, and (2) DSR. The classical type of research focuses on building and testing theories, while DSR focuses on building artefacts that could be useful to a particular actor community. DSR has its roots in engineering and fundamentally works according to a problem-solving paradigm (Baskerville et al., 2018). DSR involves the construction of a wide range of socio-technical artefacts, such as decision support systems, modelling tools, methods for IS evaluation and change intervention, and governance strategies (Gregor and Hevner, 2013). According to Hevner (2007), every DSR project should have (1) its problem, (2) its (benefitting) environment, (3) the to be designed artefact, and (4) clearly identified and defined contribution to knowledge. Baskerville et al. (2018) summarize that the DSR paradigm combines practical relevance and scientific rigor to IS research, through its emphasis on designing useful artefacts and formulating design theories.

In line with Haraldson et al. (2020), we argue that the freight transport and logistics system can be considered as a large-scale socio-technical system that consists of various functional subsystems and operates in a complex environment, which correspondingly includes a large set of participating actors. Our research can be positioned in the light of the four main DSR elements of as follows:

1 The *problem* is that current IS of ports are not able to provide the necessary visibility and interoperability, in terms of T&T of logistics operations, to fully operate in a hyperconnected PI network with its modular PI containers.
2 The *(benefitting) environment* consists of actors in the logistics chain that are involved in the shipping and trading of goods. As summarized by Sallez et al. (2016), these actors can be categorized into: *shippers and receivers, transport service providers, hubs,* and *coordinators.*
3 The to be designed *artefact* is an innovative IA, which is based on the RAMI 4.0, for the T&T function of maritime ports in the PI. A

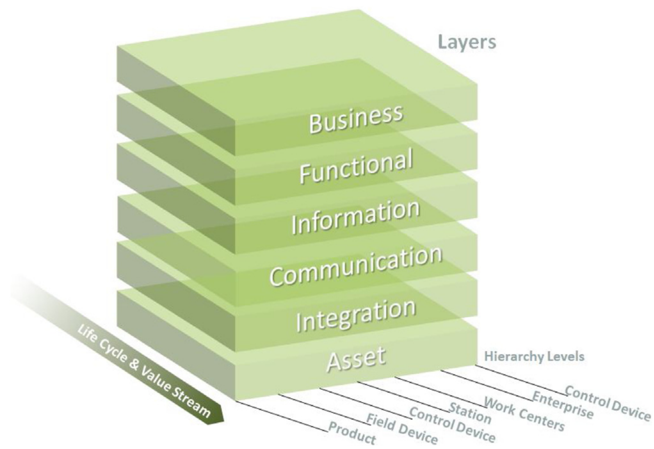

Fig. 3. Reference Architecture Model for Industry (RAMI) 4.0 (adapted from: Adolphs et al., 2015).

suitable way to test the application of RAMI 4.0 is through a use case (Adolphs et al., 2015). Hence, to keep the design rooted in a real-world situation, in Section 4, we show the applicability of the to be designed artefact through an illustrative use case.

4 The main *contribution to knowledge* of our research is the design of a tractable and reproducible IA for the T&T functionality of maritime ports in a PI context.

3.2. Reference Architecture Model for Industry 4.0 (RAMI 4.0)

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

As can be observed from Fig. 3, RAMI 4.0 comprises three dimensions that are used to view one particular (sub)system from different angles (Fleischmann et al., 2016):

- *Layers* separate the concern of interoperability, and understanding of syntax and semantics from different views. Also, the layers serve as interfaces between the physical and digital world.
- *Hierarchy Levels* enable a functional allocation of (sub)system components, and therefore, this dimension can be used as a guideline to allocate the different modules of a system. From the perspective of this dimension, the RAMI 4.0 derives its classification from the IEC 62,264 and IEC 61,512 standards.
- *Life Cycle & Value Stream (LC&VS)* allows the classification of a particular state in which the (sub)system currently finds itself in the LC&VS. From the standardization perspective of this dimension, the RAMI 4.0 derives the LC&VS from the IEC 62,890 standards.

3.3. Scoping of RAMI 4.0 for the design problem

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

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

4. Teesport as illustrative use case

In the previous section, we introduced RAMI 4.0 to design an IA for PI ports' T&T systems. In this section, we introduce the Teesport as an illustrative use case through which we aim to show the applicability of our methodology. In addition, we aim to derive requirements from the Teesport case to use for the conceptual design of the IA of the T&T system in the next section.

Teesport can be considered as an example of the Port Centric Logistics (PCL) paradigm. PCL can be defined as providing value-added services (VAS), such as product localization, warehousing and distribution, labelling, quality inspections, light manufacturing and final assembly, within port perimeters (Monios et al., 2018). Integrating VAS at ports enables logistics networks to be less complex and, among others, removes the necessity of making an extra stop at other dedicated logistics centers. PCL has been argued to be the main concept of the next generation (in the evolution) of ports (Monios et al., 2018). From this perspective, PCL can be regarded as an early generation PI port, which is expected to be an increasingly dominant, active and intelligent agent in the logistics chain through the dynamic exchange of goods and information with its actors (Montreuil et al., 2018). We investigated the concept of PCL and its current practical implementations to understand potential useful contributions of the three PI components of (1) encapsulation, (2) interfaces, and (3) protocols. Encapsulation through modularization is expected to, among others, contribute to decreasing the number of used containers through improved space utilization. By the use of interfaces and standard protocols (in T&T systems), both visibility of PI containers in- and outside the port, and interconnectivity between ports, and between ports and other actors in the logistics chain are expected to be enhanced.

4.1. Position of Teesport in the logistics chain

Fig. 4 shows that Manufacturer X, which is a Shanghai based T-shirt and swimsuit manufacturer, and Manufacturer Y, which is a Hong Kong based television manufacturer, ship their products through the Port of Shanghai and Port of Hong Kong, respectively, by means of maritime container transport to Teesport, the port of discharge. Once arrived at Teesport, the shipments will be repositioned according to their next or final destination, as for example the Retailer's distribution center (DC), and will continue their journey.

4.2. Envisioned operations at Teesport

Fig. 5 shows a more detailed schematic of an example of envisioned decompositioning and (re-)compositioning operations at Teesport. Two T-containers arrive at Teesport from the Port of Shanghai and Port of Hong Kong. As indicated by the orange, green, and blue rectangles, once the *inbound T-containers* arrive at

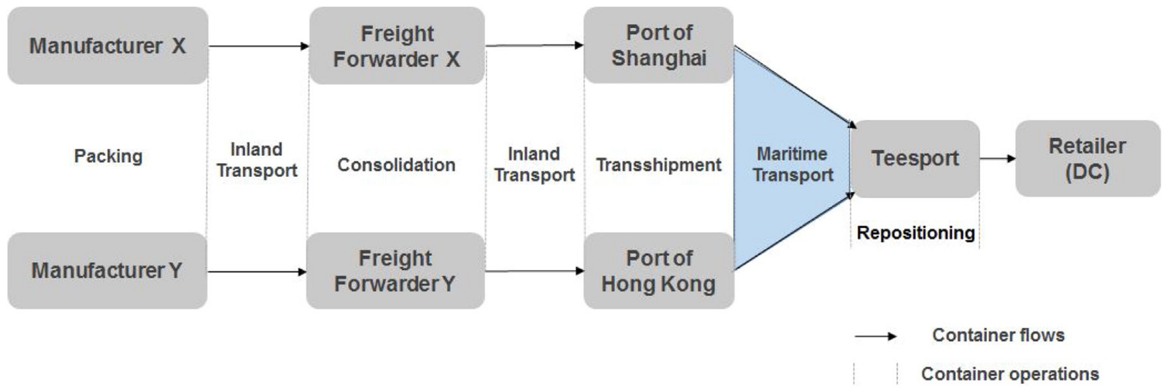

Fig. 4. The logistics chain of the Teesport case.

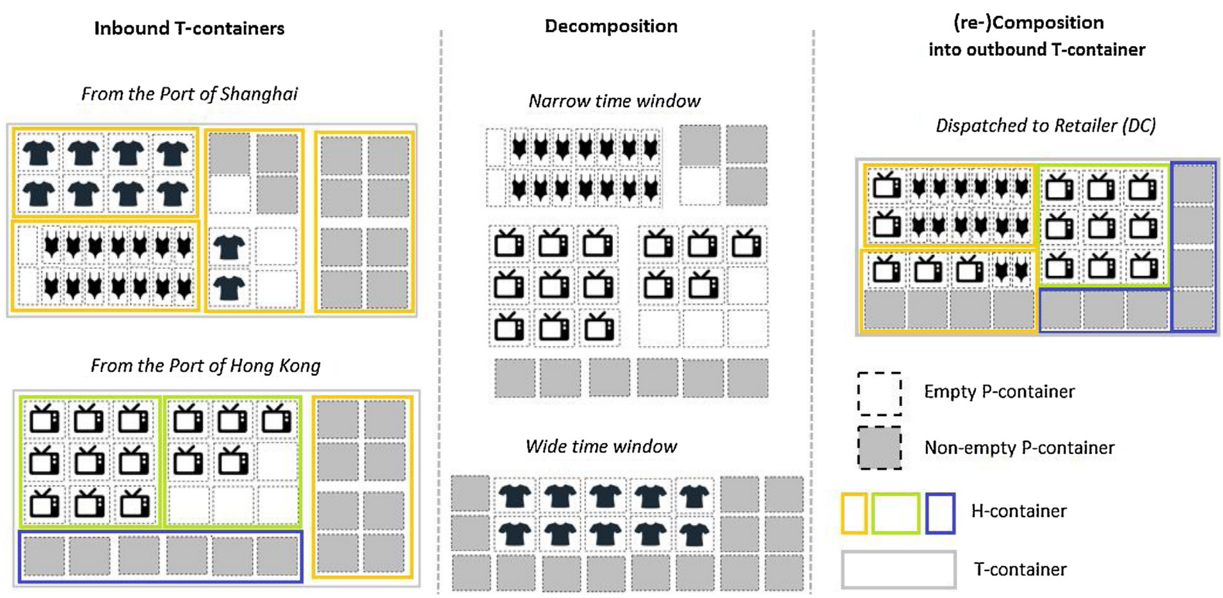

Fig. 5. Decompositioning and (re-)compositioning operations at Teesport.

Teesport, they are decomposed in the *Decomposition* phase. Next, P-containers and H-containers, are, again, composed (or consolidated) into H-containers and T-containers in the *(re-)Composition* phase according to their optimal routing and consolidation opportunities, which are determined, among others, by the variables of final destination and desired time-window. Here, P-containers and H-containers are composed into a T-container in such a way that space is optimally utilized, and they are ready to be dispatched to the retailer's DC. In the meantime, the "left over" P-containers and H-containers are stored until there are enough for a next destination in a desired time window to be consolidated and dispatched.

4.3. Envisioned T&T system

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

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

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

5. Conceptual design

After having introduced the methodology in Section 3 and having presented the illustrative Teesport case in Section 4, this section proposes the conceptual design of the PI Port T&T IS' IA. However, to support this design, we first define a minimal scope for our IA design which obviates the definition of specific technologies for hardware and software.

5.1. Design scoping in relation to the full RAMI 4.0 framework

In line with the scoping of our research in Section 3, inspired by Fleischmann et al. (2016), our design will operationalise a reduced version of RAMI 4.0 (see Fig. 6), which includes the dimensions of *layers* and *hierarchy levels*. As we want to emphasize the exchange of information and stay clear from a discussion of specific technologies to store and exchange information, our focus is on the design of the *Asset, Information* and *Functional* layers of the IA, given the needs identified in the *Business* layer. We argue that our design is neutral to technology choices made in the *Integration* and *Communication* layers. In a second-round design, a follow-up on this research will be needed to contemplate alternatives, evaluate them (based on the ability to support this IA and on criteria like technology readiness), and specify these layers in detail.

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

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

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

5.2. Business layer

The Business layer refers to the business processes, and describes the logistics operations as would happen in the PI, to have a clear starting point for the design of the underlying information processes. Here, we further build upon the foundations of the business processes and logistics operations that have been illustrated in the Teesport case of Section 4. Fig. 7 visualizes the operational processes of a part of a logistics chain in the PI, using a Business Process Model and Notation (BPMN) diagram that starts at a port terminal and ends at a consignee. A major difference in the processes with the today's situation is the presence of various levels of PI containers (P/H/T-containers) in PI ports. Another major difference, as also illustrated before in the Teesport case, is the absorption of (some of) the VAS, such as decompositioning and (re-)compositioinng of PI containers by PI ports. The blue-highlighted operations in Fig. 7 specify the new and PI specific operations at the port. The following assumptions hold in this design of the operational processes:

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

Fig. 7 shows that the business processes include new operational activities related to decision making, the acquisition of decision-making information, and the publishing of updated information that results from the implementation of these decisions. All these serve the de- and recompositioning of PI containers, at different levels of modularity, as the needs arise.

5.3. Functional layer

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

This layer is modelled by means of an Activity Diagram, as shown in Fig. 8. Aiming at the major T&T functions, the figure shows the internal elements of the T&T systems in ports, the external elements of the PI OI, and the user of the PI OI. In addition, it shows the interaction between different elements inside the T&T system and the PI OI, and between these systems. Information flows are used as primary input of these activities and interactions.

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

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

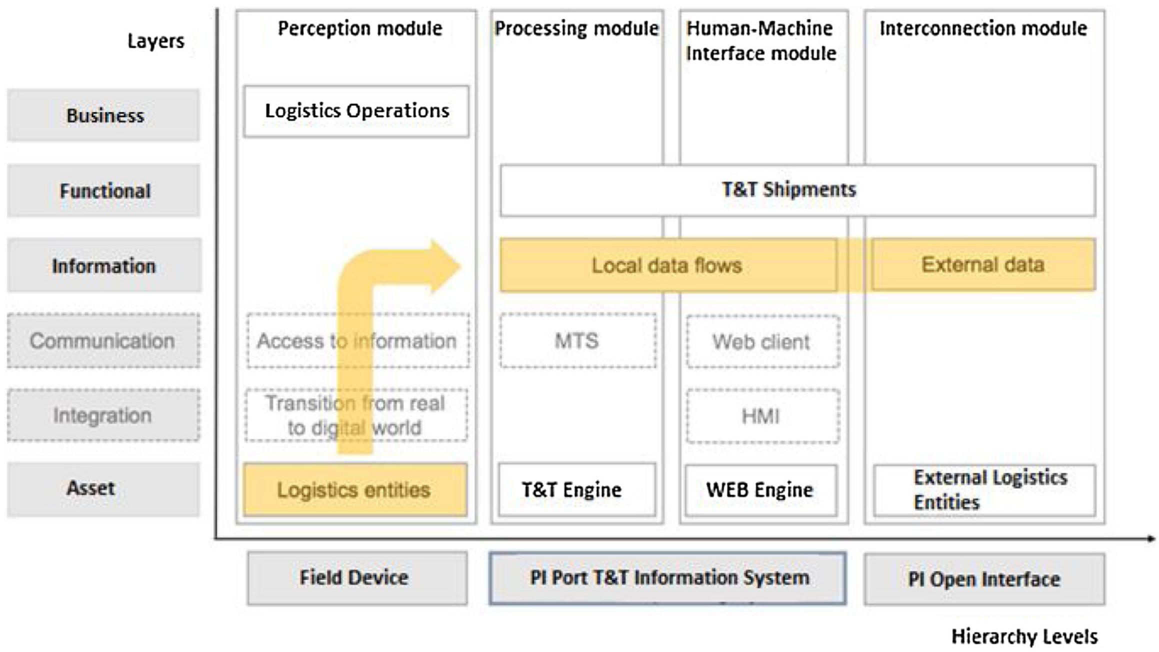

Fig. 6. Adapted version of RAMI 4.0 for the T&T system of PI Ports.

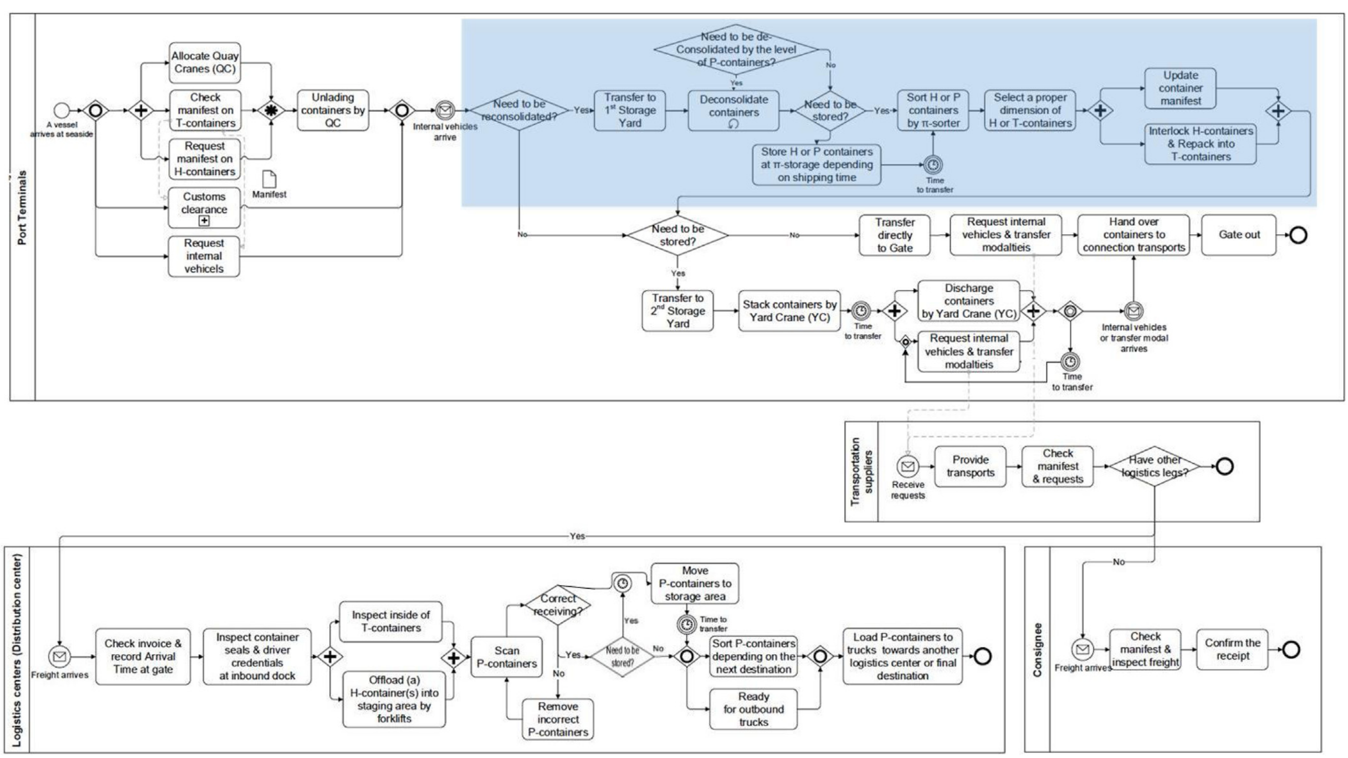

Fig. 7. BPMN-diagram of Envisioned Operational Process from the Business Layer.

how data is used to compose the information elements support the Functional layer.

5.4. Information layer

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

Fig. 9 shows the context diagram of the Information layer, and provides a formal description of rules and the execution of event-related rules. These rules initiate processing of information in the Functional layer. In our case, local and external data flows between internal and external logistics actors and entities are the main subject of this layer. The data flows reflect the interdependencies

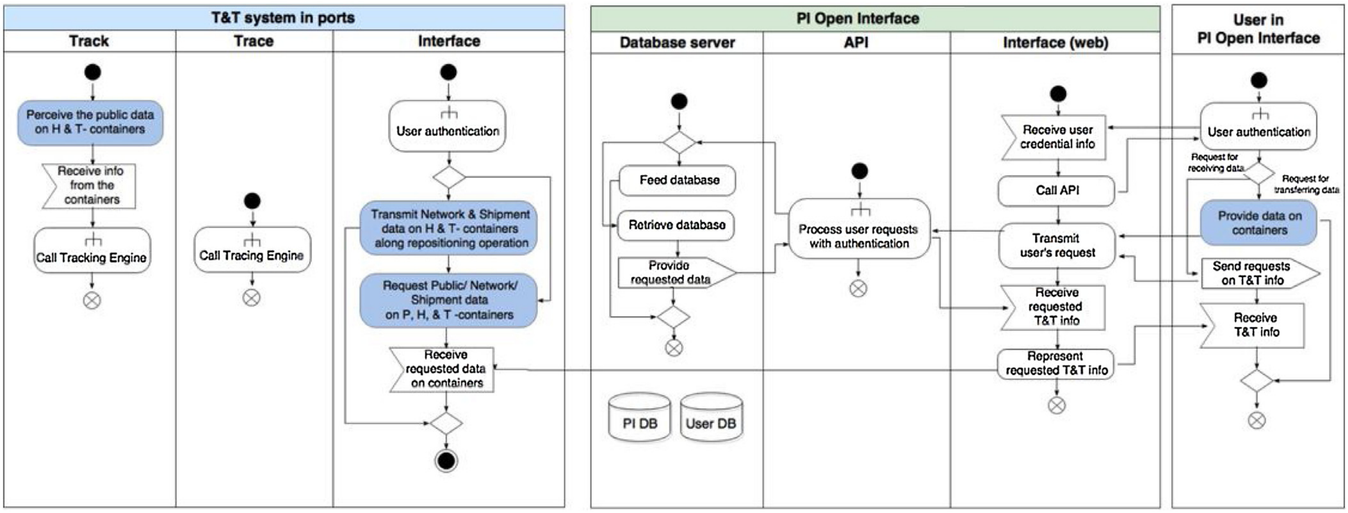

Fig. 8. Activity diagram for the Functional Layer of PI Ports' T&T Information Architecture.

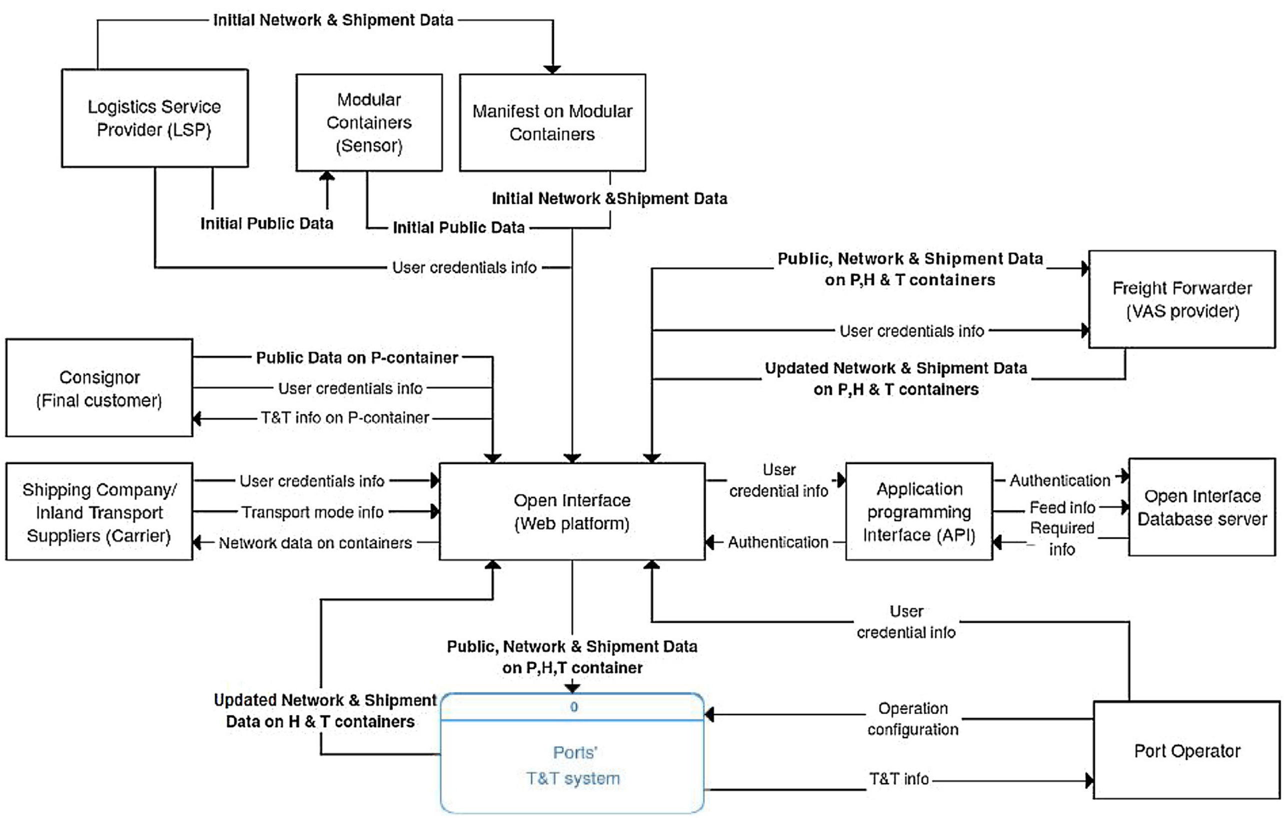

Fig. 9. Context diagram for the Information Layer of PI Ports' T&T Information Architecture.

between the T&T system of a port, the PI OI (Web Platform), and the other logistics entities. In contrast with current systems, PI ports send user credential information to the PI OI (Web Platform) for authentication and authorization of data, and not directly to other logistics actors in a bilateral manner. In the PI OI (Web Platform), the API authenticates the PI port and retrieves data from the PI OI's DB server. The information from the DB server is transferred the other way around from the DB to the PI OI through the API.

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

5.5. Asset layer

The Asset layer within RAMI 4.0 describes the attributes of the physical assets, such as, for example, components, machines and factories of a system. In our case, it is designed to clarify the characteristics and relationships of logistics entities such as vessels, PI containers and various types of terminal equipment, such as quay cranes, yard cranes, and other internal vehicles. We build on the entities as we envision them in a PI port, to be able to support all the higher-level layers of the AI in a PI context. Assuming that T&T systems of PI ports are interconnected with the PI OI as a web-based platform, ports are enabled to communicate the internal T&T information of PI containers with other logistics actors and entities. Information flows of PI containers fulfil the functions of T&T via the local T&T interface, where the PI DB and the User DB are the intermediate steps of the information flows through the PI OI (see Fig. 8).

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

6. Discussion

With respect to the overall approach, we positioned our research in the light of the four main elements of DSR in Section 3. We designed a new artefact in terms of an IA based on RAMI 4.0, which benefits the actors in the logistics chain, and satisfies the PI's requirements. We show that the use of RAMI 4.0 facilitates systematic reasoning and its applicability by means of the Teesport case. The IA presented in this paper highlights the organization, functions, interactivity of, and interaction between the information flows inside the port and with the PI OI. The main design limitations of the work are twofold. As the details of its implementation are not demonstrated yet in real life, the performance of the proposed IA cannot be validated and evaluated. However, the functional illustration of the IA in the Teesport case provides insights into the functioning of the IA in practice and its benefits for PI ports and its actors. Another clear limitation of our design, although for justifiable reasons which are explained in Section 3, is the exclusion of the Communication and Integration layers.

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

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

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

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

7. Conclusions and future research

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

The IA design approach allows us to explore the potential of key PI elements for ports to cope with future challenges in the

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

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

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

Author statement

We would like to thank you for the opportunity to submit a revised version of our manuscript, *An Information Architecture to Enable Track-and-Trace Capability in Physical Internet Ports*.

We are very grateful for the valuable comments of the reviewers, which we have incorporated into the revised version of our manuscript as well as we could. In addition, we attached a response letter to the reviewers' comments, in which we explain our response to each of the reviewers' comment.

Thank you, again, for the opportunity to improve and submit a revised version, and thank you for your consideration for publication.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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