POLITECNICO DI TORINO

Master of Science in

Management Engineering

Master Thesis

Information Exchange in a Physical Internet Network: A proposed architecture

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To my Family, endlessly grateful

ABSTRACT

The Physical Internet (PI) is an innovative system that aims to revolutionize current paradigms of global logistics. It is founded on the designing principles of the Digital Internet, such as transparency, resource sharing, and information exchange, with the goal of creating a more efficient and environmentally friendly logistics network. Unlike the Digital Internet, where network packets contain routing information within them, the PI operates differently. It requires a network of communication protocols to support global interconnection and collaboration to ensure effective delivery to the destination.

In this regard, this thesis defines a categorization of communication protocols analysing the nature of messages exchanged within the PI. Through a systematic literature review of Physical Internet protocols guided by the aforementioned categorization, an effort has been made to specifically deduce what essential information is exchanged during logistic processes and how it is exchanged. Although the literature often focuses on the types of messages exchanged, it often remains vague and confusing when discussing a messaging system capable of supporting the universal interconnection promised by the Physical Internet.

Therefore, this thesis aims to propose a hybrid data exchange system based on Publish-Subscribe (Pub/Sub) systems and point-to-point communication where it is required. A platform of this kind, with an open data structure, allows various actors within the PI to share information with the network and access specific information that the network possesses. This typology of system overcomes the need for point-to-point communication, at least for most of the logistics processes, and enable end-to-end visibility and traceability for pi-actors through ubiquitous information exchange.

Summary

1. Introduction

In an era defined by unprecedented global connectivity and the ongoing evolution of technology, the logistics and transportation sectors are facing immense challenges in meeting the demands of a rapidly changing world. As traditional supply chain models strain under the pressure of increasing urbanization, rising consumer expectations, and environmental concerns, a visionary concept has emerged to revolutionize the way goods are moved and managed: the Physical Internet (PI, π).

In Montreuil, Meller, & Ballot (2012) authors define this concept as following:

> "We define the Physical Internet as an open global logistics system founded on physical, digital, and operational interconnectivity through encapsulation, interfaces, and protocols. It is a perpetually evolving system driven by technological, infrastructural, and business innovation."

As we can infer from these words the Physical Internet proposes a paradigm shift from the traditional linear supply chain model to an open, interconnected, and modular system. At its core, the Physical Internet draws inspiration from the best-known network of networks with an open and interconnected architecture, the Digital Internet. Indeed, the PI envisages a global logistics ecosystem built on principles of modularity, standardization, collaboration, and efficiency. Just as the digital internet enables the seamless exchange of information across a network of interconnected devices, the Physical Internet aims to achieve a similar level of efficiency, collaboration, and sustainability in the global logistics and supply chain networks.

Therefore, the key principles the Physical Internet lies its foundation on are:

- **Modularity and Standardization:** just as digital information is broken down into packets of data that can be easily shared and reassembled, physical goods would be encapsulated in specific pi-containers, modularized and standardized. This allows for greater flexibility and ease of combining different shipments and modes of transportation.
- **Open Networks:** similar to the open architecture of the internet, the Physical Internet promotes open access and collaboration among various stakeholders, including manufacturers, shippers, carriers, and consumers.
- **Decentralization:** Physical Internet envisions a decentralized network where assets (containers, vehicles, warehouses, etc.) are shared and utilized more efficiently, reducing the need for excessive redundancy, and lowering costs.

- **Smart Technologies:** emerging technologies such as the Internet of Things (IoT), artificial intelligence (AI), and advanced data analytics play a crucial role in optimizing the movement of goods, tracking shipments, and predicting demand.
- **Efficiency and Sustainability:** by minimizing empty runs, optimizing routes, and reducing congestion, the Physical Internet aims to improve the overall efficiency of transportation and logistics operations, leading to decreased energy consumption, emissions, and environmental impact.
- **Collaborative Logistics Ecosystem:** the concept encourages collaboration among stakeholders, fostering new business models and partnerships that enhance efficiency and create value.

In order to simplify the understanding of the next chapters below we will define the most important actors taking part in the Physical Internet system.

In the context of the Physical Internet (PI), a pi-node refers to a critical component of the PI network infrastructure. PI-nodes are physical locations or hubs within the PI ecosystem where goods are received, processed, transferred, and dispatched as they move through the interconnected logistics and transportation network envisioned by the Physical Internet concept. PI-nodes serve as hubs or centers where goods are both received and dispatched. They play a pivotal role in the efficient transfer of goods between different carriers and modes of transportation. At PI-nodes, goods can be consolidated (combined) from multiple shippers or deconsolidated (split) for onward transportation. This allows for efficient routing and grouping of shipments. PI-nodes adhere to standardized processes and technologies to ensure compatibility and smooth transitions between different elements of the Physical Internet network. This includes standardized container sizes and handling equipment (pi-conveyors, pi-vehicles). PI-nodes are equipped with advanced information technology systems to enable real-time data sharing and coordination. This data helps optimize the routing and scheduling of goods through the network.

On the other hand, a pi-carrier is an entity or organization responsible for physically moving goods (by pi-means) within the interconnected and collaborative PI network. These carriers are a key component of the PI ecosystem, working alongside shippers and other stakeholders to facilitate the efficient and sustainable movement of goods. PI-carriers work to optimize their routes and schedules to minimize empty or underutilized cargo space and reduce transportation costs. They collaborate with other carriers and logistics providers to share resources and assets when necessary.

Finally, a pi-shipper refers to an entity or organization that sends goods or products through the interconnected and collaborative logistics and transportation network envisioned by the Physical Internet concept. PI-shippers are key participants in the PI ecosystem and play a crucial role in the efficient and sustainable movement of goods within this framework. PI-shippers initiate the movement of goods within the Physical Internet network after having received goods to ship from the customer. PI-shippers may work with various logistics providers, carriers, and service providers within the Physical Internet network to transport their goods. This could involve selecting the most efficient start pi-node (pi-entry-gateway) performing encapsulation and first routing services. PI-shippers contribute to the real-time data sharing and visibility within the network. They provide information about their shipments, such as item descriptions, destination, and desired delivery times, to facilitate optimal routing and scheduling.

At this juncture, the successful adoption of the Physical Internet hinges on the development and deployment of robust and adaptable protocols. In the context of the Physical Internet, protocols refer to standardized rules, procedures, and guidelines that govern the movement, handling, and interaction of physical goods and resources within the global supply chain. The main purpose of these protocols is to enable the creation of a synchronized and coordinated global network for the movement of goods, similar to how the Digital Internet enables seamless communication and data exchange. By having standardized protocols, different players in the supply chain — manufacturers, transporters, distributors, and more — can work together effectively without the need for extensive one-to-one or complex many-to-many collaboration agreements for every interaction. Instead of relying on case-by-case collaboration contracts, the coordination in the Physical Internet is achieved through adherence to the established protocols. These protocols define various aspects of the logistics process, such as container sizes, handling procedures, routing services and more. When all participants follow these protocols, a high degree of coordination is naturally achieved, resulting in smoother operations, reduced delays, and improved efficiency.

1.1 Thesis Structure

This dissertation will be structured into five main chapters following the introduction. The first chapter will outline the research gap we identified, the research questions this thesis is intended to answer and the objectives it sets. The second chapter will address an overview of the methodology used to reach our research objectives. Therefore, it will illustrate a systematic literature review. Moreover, for each paper this chapter will provide an extensive paragraph aimed at explaining their point of view, as far as PI protocols are concerned. Therefore, this section will clarify the contribution that each publication provides to the discussion regarding Physical Internet protocols. At the end of these paragraphs (most of them, not all), a series of graphs will schematically illustrate the resource exchange (mostly flow of data) and protocols proposed by the authors in the various papers. The third chapter will proceed revealing the results of this dissertation. A critical analysis of the literature was performed following the structure of a categorization of messages (flowing during PI logistics processes) proposed therein trying to understand which typology of messages and data are necessary to be exchanged. Furthermore, the third chapter proposes an innovative and hybrid data exchange system able to support most of analysed data exchanges. This data exchange system will be theoretically validated in the fourth chapter with some use-cases. Finally, with the fifth chapter, the intention is to finally discuss the main results that have emerged from the analyses and the model proposition.

2. Research Gap and Thesis Objectives

During the study of different scientific papers on the Physical Internet, a noticeable research gap emerged concerning the communication protocols, at various levels, vital for the functioning of the 'open global logistics system' conceptualized by Montreuil (2012). Although the analysed literature often focuses on outlining PI protocols supported by continuous data exchange and thus characterized by universal interconnectivity (a key concept supporting the Physical Internet), a precise and exhaustive explanation of the nature of these exchanged messages and, most importantly, the system supporting such exchanges was often lacking or rather confusing. Therefore, the following research questions emerged:

- **Rq1:** What information is transmitted to make the PI function? Is it possible a sort of categorization of data/messages exchanged?
- **Rq2:** How is this information exchanged?

In order to address these research questions, a systematic analysis of the literature was necessary. The analysis aimed to identify within the literature a well-established, shared, and structured communication model and protocol. In this regard, this analysis made it possible to establish a categorization of the primary communication protocols (in the context of PI) and the types of messages that constitute the flow of data and information exchanged within the Physical Internet. The categorization served as an initial framework for conducting a critical analysis of the literature, offering a structured and organized approach. This research work was aimed at analysing how different categories of communication protocols were discussed in the analysed publications in order to detect inconsistencies and precious insights.

Finally, given the poor and confused contribution received from the literature on this topic, the ultimate objective of this research work was the conception and definition of an innovative data and messages exchange system aimed at outlining the essential protocols for managing physical and digital resources within this new global logistic paradigm, with a particular focus on network information sharing and accessing.

3. Methodology

3.1 Methodology introduction

We proceeded as follows: locate existing publications; select and evaluate contributions; analyse and synthesize data; and report on the findings in terms of critical analysis on different protocol and data exchange issues.

First, to locate literature on the PI and its protocols, it was used Scopus, Elsevier's abstract and citation database. Therefore, in order to limit the number of publications on the PI, Scopus query tool was asked to return papers with "Protocols" in Article Title, Abstract or Keywords AND (logic operator) "Physical Internet" in the Article Title. Scopus database returned nineteen publications: conference proceedings papers, journal papers, and chapters from edited books that directly address the logistics concept "PI". From this initial pool, an initial selection was conducted for availability issues. Indeed, three publications were excluded from the research work since they were not available in the databases we have access. These excluded papers (2 chapters from edited books and 1 journal paper) are the following:

- Ballot, E. (2019), "The Physical Internet*", Lecture Notes in Logistics*, pp. 719-734
- Ballot, E., PAN, S. (2021), "The Physical Internet and Logistics", *International Encyclopaedia of Transportation: Volume 1-7,* 3, pp. 479-487
- Peng, X., Ji, S., Thompson, R.G., Zhang, L. (2021), "Resilience planning for Physical Internet enabled hyperconnected production-inventory-distribution systems", *Computers and Industrial Engineering,* 158, art. no. 107413

In addition, in the list of papers returned by Scopus query there was one duplicated journal paper that was not included twice:

- B. Montreuil, R. D. Meller, E. Ballot (2012), "Physical Internet Foundations", *Studies in Computational Intelligence*, 472, pp. 151-166

Furthermore, a second selection was performed through a cautious reading and analysis activity of the remaining fifteen papers. Seven publications out of fifteen were excluded for different reasons after a first reading. Specifically, the papers excluded are:

- Y. Sun, C. Zhang, K. Dong, M. Lang (2018), "Multiagent Modelling and Simulation of a Physical Internet Enabled Rail-Road Intermodal Transport System*", Urban Rail Transit 4,* 141–154 (2018).
  - This paper was excluded since it does not provide any new insight about information exchange and protocol.
- H. Tran-Dang, K. Dong-Seong (2019), "Physical Internet for Military Logistics: Perspectives", *International Conference on Information and Communication Technology Convergence (ICTC), Jeju, Korea (South)*, pp. 755-757
  - This paper was excluded since it is a literature review about basic concepts of Physical Internet with some insight on emerging technologies prospectives, not relevant to the topic of this thesis.
- D. Soedarno, B. Ranti, W. S. Nugroho (2020), "Use of Physical Internet System to Increase Effectiveness of Sea Toll Logistics Operations in Indonesia", *6th International Conference on Interactive Digital Media (ICIDM)*
  - This paper was excluded since it makes a literature review about Physical Internet trying to conceptually adapt them to the specific case study not relevant to the topic of this thesis.
- S. Pan, M. Nigrelli, E. Ballot, R. Sarraj (2013), "Performance assessment of distributed inventory in Physical Internet", *43rd International Conference on Computers and Industrial Engineering (CIE43)*
  - This contribution measures the impact of a Physical Internet network on inventory levels and inventory costs. Therefore, it is not relevant to the topic of this thesis.
- H. S. Sternber, N. Denizel (2021), "Toward the Physical Internet—Logistics Service Modularity and Design Implications", *Journal of Business Logistics*, 42(1): 144–166

    - Evaluates how the design and physical characteristics of containers determine the flow of pi-containers in a home network. As a consequence, this publication is out of scope for our research.
- Y. Sallez, T. Berger, T. Bonte, D. Trentesax (2015), "Proposition of a hybrid control architecture for the routing in a Physical Internet cross-docking hub", *International Federation of Automatic Control (IFAC)*
    - This paper was excluded since doesn't provide insights about information exchange and protocols.
- H. Tran-Dang, D. S. Kim (2021) "The Physical Internet in the Era of Digital Transformation: Perspectives and Open Issues," in *IEEE Access*, vol. 9, pp. 164613-164631
    - This paper was excluded since doesn't provide insights about information exchange and protocols.

Furthermore, our review was enriched by seven publications frequently referenced or complementary to other conference articles. Finally, we compared our review with another review of the PI by Sternberg & Norrman, (2017) to ensure that the most relevant sources were included in our review.

In total, 15 publications were selected for the review (8 from Scopus query and 7 from frequently referenced publications – details in Table 1): 4 conference proceedings papers, 7 journal papers and 4 chapters from edited books (details in Table 2).

AUTHORS	YEAR	PUBLICATION TITLE
B. Montreuil, E. Ballot, F. Fontane	2012	An Open Logistics Interconnection Model for the Physical Internet
R. Sarraj, E. Ballot, S. Pan, B. Montreuil	2012	Analogies Between Internet Networks and Logistics Service Networks: Challenges Involvdd in the Interconnection
B. Montreuil, R. D. Meller, C. Thivierge, Z. Montreuil	2012	Functional Design of Physical Internet Facilities: A Road-Based Crossdocking Hub
B. Montreuil, R. D. Meller, C. Thivierge, Z. Montreuil	2012	Functional Design of Physical Internet Facilities: A Road-Based Transit Center
B. Montreuil, R. D. Meller, E. Ballot	2012	Physical Internet Foundations
E. Ballot, B. Montreuil, C. Thivierge	2013	Functional Design of Physical Internet Facilities: A Road-Rail Hub
R. Sarraj, E. Ballot, S. Pan, D. Hakimi, B. Montreuil	2014	Interconnected Logistic Networks and Protocols: simulation-based efficiency assessment
C. Pach, Y. Sallez, T. Berger, T. Bonte, D. Trentesaux, B. Montreuil	2014	Routing Management in Physical Internet Crossdocking Hubs: Study of Grouping Strategies for Truck Loading

J. Colin, H. Mathieu, M. Nakechbandi	2016	A Proposal for an Open Logistics Interconnection Reference Model for a Physical Internet
S. Gontara, A. Bounfaied, O. Korbaa	2018	Routing the PI-Containers in the Physical internet using the PI-BGP Protocol
T. Chargui, A. Bekrar, M. Reghioui, D. Trentesaux	2019	Multi-Objective Sustainable Truck Scheduling in a Rail-Road Physical Internet Cross-Docking Hub Considering Energy Consumption
Marlam Lafkihi, Shenle Pan, Eric Balot	2019	Rule-based incentive mechanism design for a decentralized collaborative transport networl
H. Tran-Dang, N. Krommenacker, P. Charpentier, D. Kim	2019	Toward the Internet of Things for Physical Internet: Perspectives and Challenges
S. Kaup, A. Ludwig, B. Franczyk	2021	Framework Artifact for the Road-Based Physical Internet based on Internet Protocols
M. Briand, R. Franklin, M. Lafkihi	2022	A Dynamic Routing Protocol with Payments for the Physical Internet: A simulation with learning agents

Table 1 Complete list of Analysed Papers

Type of publication	N. Papers	Authors
Conference proceedings paper	4	Montreuil, Ballot and Fontane (2012); Colin, Mathieu, Nakechbandi (2016); Gontara, Bounfaied and Korbaa (2018); Kaup, Ludwig, Franczyk (2021);
Journal Paper	7	Sarraj, Ballot, Montreuil (2012); Montreuil, Meller, Ballot (2012); Sarraj, Ballot, Pan, Hakimi, Montreuil (2014); Chargui, Bekrar, Reghioui, Trentesaux (2019); Lafkihi, Pan, Ballot (2019); Tran-Dang, Krommenacker, Charpentier, Kim (2019); Briand, Franklin, Lafkihi (2022)
Chapter from edited book	4	Montreuil B., Meller, Thivierge, Montreuil Z. (2012a); Montreuil B., Meller, Thivierge, Montreuil Z. (2012a); Ballot, Montreuil, Thivierge (2013); Pach, Sallez, Berger, Bonte, Trentesaux, Montreuil (2014);
Totale	15	

Table 2 Types of Publication

Overview of publications

A variety of research methods have been used in the reviewed publications (see Table 2). Some papers are conceptual (e.g. Montreuil, Ballot and Fontane, 2012; Montreuil et al., 2012a; Montreuil et al., 2012b; Montreuil, Meller and Ballot, 2012; Ballot, Montreuil and Thivierge, 2013; Colin et al., 2016; Kaup et al., 2021); others use simulation (Patch et. al., 2014) or mathematical modelling (Chargui et al. 2019). Another uses both case study and simulation (Gontara, Bounfaied and Korbaa, 2018). Some papers are conceptual and use both simulation and mathematical modelling (Sarraj et al., 2012; Sarraj et al., 2014; Lafkihi, Pan and Ballot, 2019; Briand, Franklin, Lafkihi, 2022). Finally, one papers give conceptual insights while reviewing literature on the PI (Tran-Dang et al., 2019).

Research Method	N. Papers	Authors
Conceptual	12	Montreuil, Ballot, Fontane (2012); Montreuil B., Meller, Thivierge, Montreuil Z. (2012a); Montreuil B., Meller, Thivierge, Montreuil Z. (2012a); Montreuil, Meller, Ballot (2012); Sarraj, Ballot, Montreuil (2012); Ballot, Montreuil, Thivierge (2013); Sarraj, Ballot, Pan, Hakimi, Montreuil (2014); Colin, Mathieu, Nakechbandi (2016); Lafkihi, Pan, Ballot (2019); Tran-Dang, Krommenacker, Charpentier, Kim (2019); Kaup, Ludwig, Franczyk (2021); Briand, Franklin, Lafkihi (2022)
Simulation	5	Sarraj, Ballot, Montreuil (2012; Sarraj, Ballot, Pan, Hakimi, Montreuil (2014); Pach, Sallez, Berger, Bonte, Trentesaux, Montreuil (2014); Gontara, Bounfaied, Korbaa (2018); Lafkihi, Pan, Ballot (2019); Briand, Franklin, Lafkihi (2022);
Mathematic Modeling	5	Sarraj, Ballot, Montreuil (2012); Sarraj, Ballot, Pan, Hakimi, Montreuil (2014); Lafkihi, Pan, Ballot (2019); Chargui, Bekrar, Reghioui, Trentesaux (2019); Briand, Franklin, Lafkihi (2022)
Case Study	1	Gontara, Bounfaied, Korbaa (2018)
Literature Review	1	Tran-Dang, Krommenacker, Charpentier, Kim (2019)

Table 3 Research Methods of analysed publications

In total, 33 authors contributed to the 15 publications reviewed, with Montreuil B. (Laval University) authoring 8 and Ballot E. (Mines Paristech) authoring 6 of them. Meller and Thivierge authored 3 pubblications each while Pan, Montreuil Z., Trentesaux, Lafkihi, Tran-Dang and Kim authored 2 papers each. Pan (Mines Paristech) authoring 12. Sarraj (Mines Paristech) and Yang (Mines Paristech) authored 4 publications and Hakimi, Meller and Xu authored 3 each. Four authors authored or co-authored 2 publications, the remaining 25 authors, 1 each.

3.2 Systematic Literature Review

Physical Internet Foundations – Montreuil, Meller, Ballot – 2012

This paper represents one of the most rated and cited foundational paper and offers valuable insights into the fundamental principles of the Physical Internet. It presents a formal definition of the Physical Internet as a globally accessible logistics system that relies on interconnection at physical, digital, and operational levels, facilitated through encapsulation, interfaces, and protocols. Aligned with this definition, the paper delves into eight key foundations of the Physical Internet, providing explanations and insights. These foundations encompass the following aspects: logistics efficiency and sustainability, universal interconnectivity, encapsulation, standardized smart interfaces and coordination protocols, logistics web enabler, an open global logistics system, and innovation-driven principles.

As far as interconnectivity is concerned, authors refer to Digital Internet as a successful experience of interconnection in order to explain how it is crucial enabling physical entities, constituents, and actors to seamlessly exchange meaningful information, orders, actions across the Physical Internet. The achievement of universal interconnectivity within the Physical Internet relies on the integrated utilization of encapsulation, interfaces, and protocols. Indeed, by leveraging encapsulation, interfaces, and protocols in a coordinated manner, universal interconnectivity becomes attainable, allowing for efficient communication and interaction among all components and entities within the Physical Internet.

Moreover, the Physical Internet conceptualizes the so-called encapsulation of physical objects in physical packets or containers (namely pi-containers or π-containers). These pi-containers are meant to be world-standard, smart, modular, and designed to be easy to load, unload, handle, seal, transport, and interlock with each other. Once the freight enters in the Physical Internet, the pi-container (physical object therein encapsulated) becomes the fundamental shipping unit to manage.

A key point, especially for the purpose of this thesis, that the authors address in this paper is the cruciality of interfaces in this new Physical Internet paradigm. Four types of interfaces are presented here: fixtures, devices, nodes, and platforms. At the fundamental physical level, the seamless flow of π-containers within the Physical Internet relies on functionally standardized and modular physical fixtures, allowing for interlocking with other containers and easing loading, unloading, consolidation activities since π-carriers, π-stores, and π-conveyors, possesses complementary fixtures to facilitate their functionality. Moving to the information and communication level, devices play a crucial role as interfaces. Each smart π-container is equipped with a smart tag that serves as its representative agent, connected to the Internet of Things. This smart tag ensures accurate information encoding, contributing to the identification, integrity, routing, conditioning, monitoring, traceability, and security of each π-container. These services can be accessed by all actors, allowed from protocols, like pi-nodes, pi-carriers, pi-shipper, and operators of these systems (Montreuil 2010). At a higher operational level, logistics π-nodes represents critical interfaces since π-gateways enable efficient and controlled entry and exit of π-containers into and from the Physical Internet. Moreover, π-transits facilitate smooth unimodal and multimodal transfers of π-carriers between π-vehicles. Instead, pi-hubs allow seamless transfers of π-containers from one carrier to another along their journey through the Physical Internet. Standardized operational interfaces at these logistics π-nodes are pivotal for ensuring scalability, guaranteeing consistent interactions regardless of location. On the information and communication level, digital middleware platforms enable an open market for logistics services within the Physical Internet and ensure smooth systemic operations for pi-constituent interaction and routing of π-containers from source to destination. These π-platforms facilitate various types of interfacing, including human-human, human-agent, and agent-agent interactions. Most common inputs for these platforms are: delivery requests (destination, target arrival, budget), shipment services requests, actors involved with records about performances, prices (assigned budget), action scheduled yet, routes planned, contracting preferences etc. Instead, outputs delivered can be: routes, identification numbers, monitoring variables (speed, service level, reliability, safety, security), best carrier chosen based on different variables (best route, best performances, best fit with delivery requests and constraints), standardized business contracts and incoterm-type modalities

The last foundation of PI we want to address here, is standard coordination protocols. They lay the foundation for actors and services interactions enabling coordination among networks without demanding one-to-one collaborative agreements. The adherence and respect to protocols guarantees coordination and fairness of interactions. Authors define three levels of protocols: basic, higher-level, highest-level protocols:

- *Basic protocols* play a crucial role in ensuring the physical integrity of π-containers and other physical constituents within the Physical Internet. They validate and guide the transfer of π-containers between various constituents. Following Internet-of-Things guidelines, a universal protocol assigns a unique identification number to each π-container and π-constituent.
- *Higher-level protocols* focus on maintaining the integrity and performance of the π-networks, routing π-containers through these networks, and managing shipments and deployments within the Physical Internet. These protocols include pi-contracting protocols that utilize standardized pi-contract formats for logistics services within the Physical Internet. They can be viewed as extensions of existing International Commercial Terms (INCOTERMS).

  A critical set of protocols ensures live, open monitoring of the performance achieved and anticipated by all actors and constituents within the Physical Internet. These protocols focus on key performance indicators such as speed, service level, reliability, safety, and security. By promoting transparency, this protocol set ensures that logistics decisions are grounded in factual evidence.

- At the *highest level*, a *protocol* is employed for multi-level certification of Physical Internet capabilities. This certification process encompasses containers, handling systems, vehicles, devices, platforms, ports, hubs, roads, cities, regions, protocols, processes, and more. It ensures that the various components and entities within the Physical Internet meet the necessary standards for their respective capabilities.

The Physical Internet, as a network of interconnected networks, needs to ensure its own reliability and resilience, as well as that of its containers and shipments. This is achieved through its inherent nature, protocols, and structure. The interconnectedness of networks and the proliferation of nodes within the Physical Internet are designed to enhance its robustness and resilience against unexpected events. In the event of a node failure or network disruption, protocols are in place to facilitate seamless and automated re-routing of π-containers to minimize disruption and maintain continuity of operations.

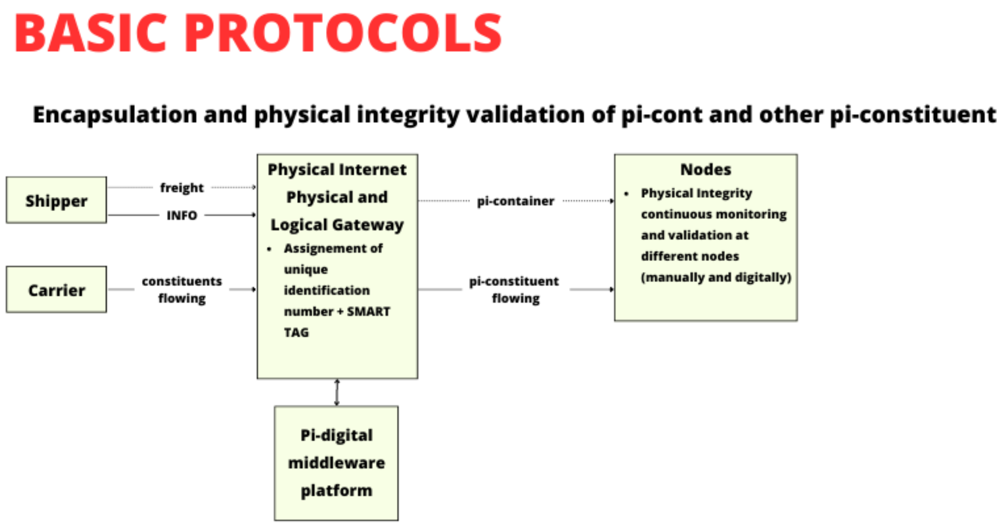

Figure 1 Basic Protocols by (Montreuil, Meller, & Ballot, 2012)

HIGHER-LEVEL PROTOCOLS

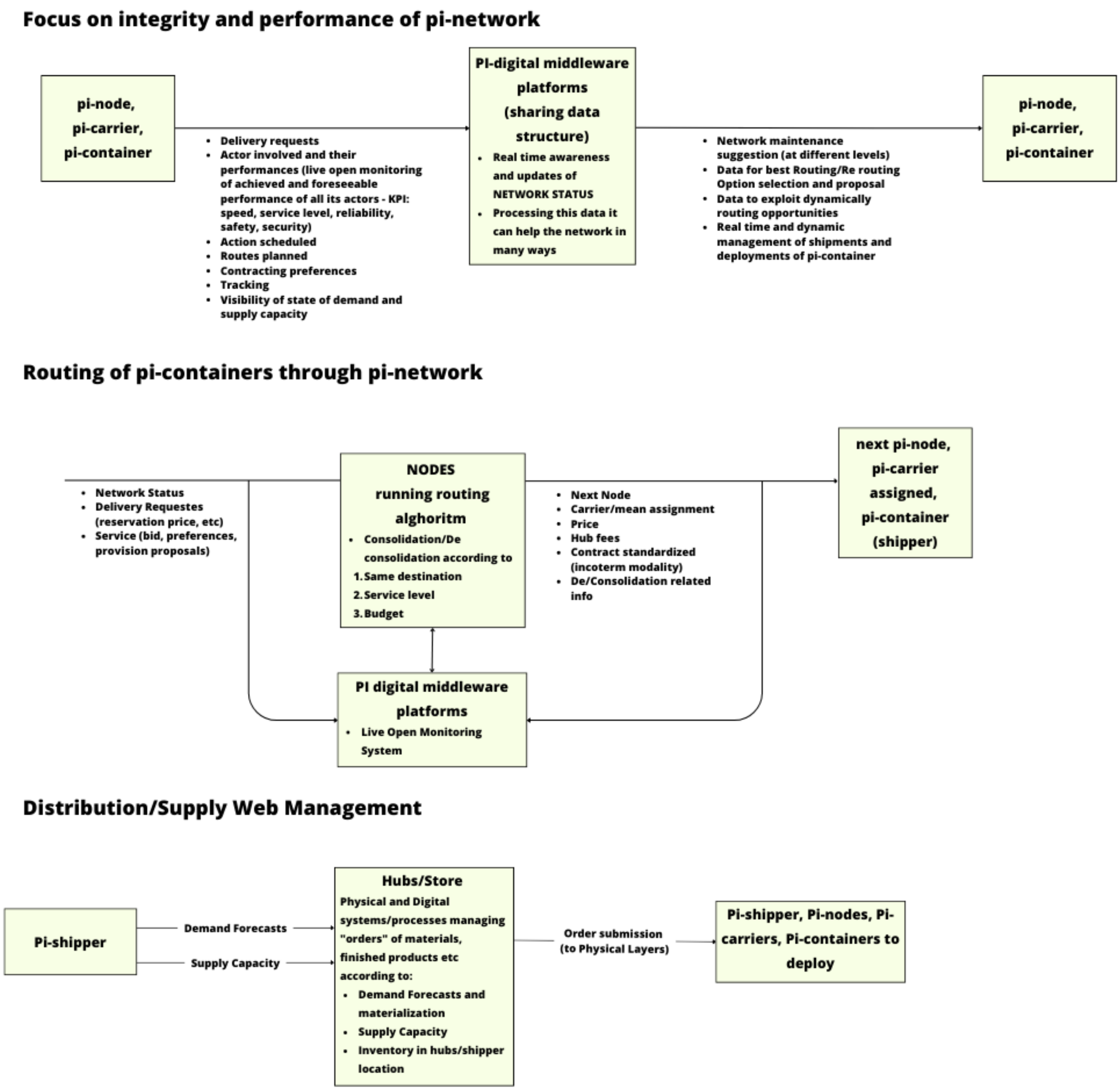

Figure 2 Higher-Level Protocols by (Montreuil, Meller, & Ballot, 2012)

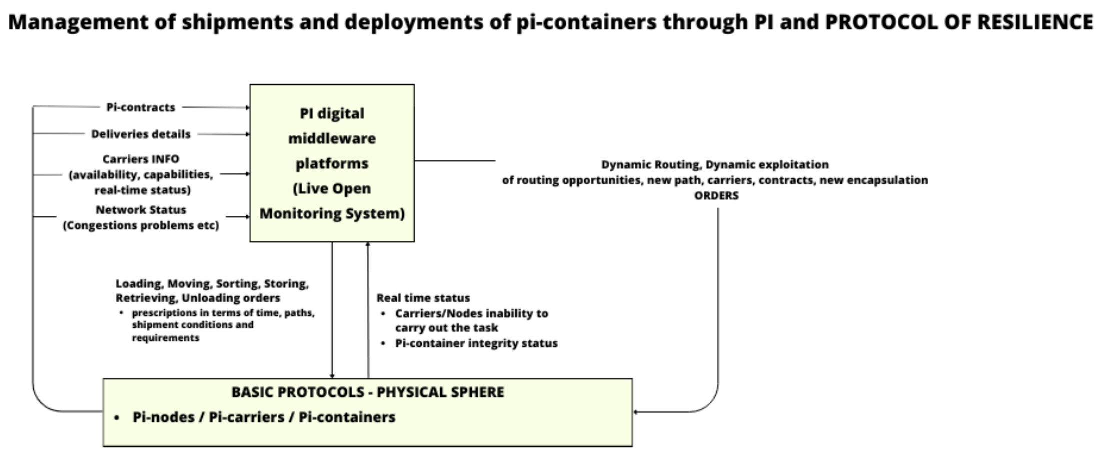

Figure 3 Higher-Level Protocols by (Montreuil, Meller, & Ballot, 2012)

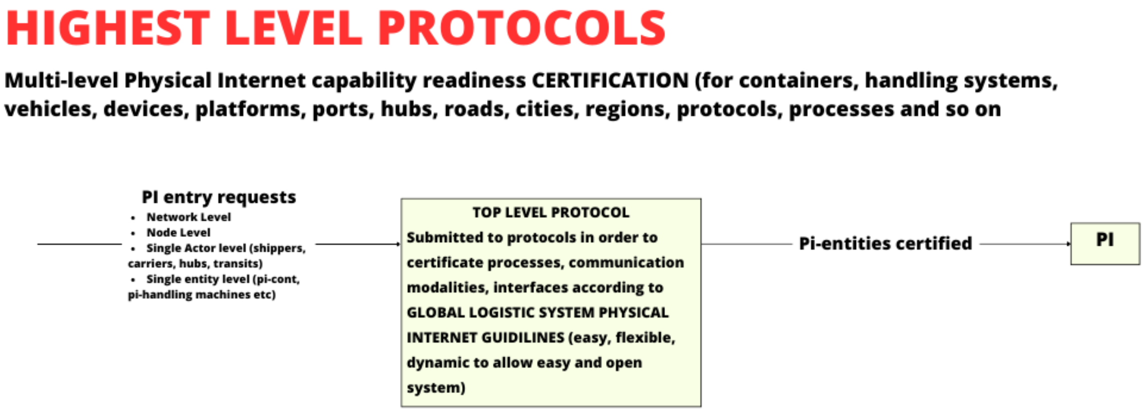

Figure 4 Highest-Level Protocols by (Montreuil, Meller, & Ballot, 2012)

An Open Logistics Interconnection Model for the Physical Internet – Montreuil, Ballot, Fontane – 2012

According to this publication, the successful experience of Digital Internet and its structured and standardized approach to networks interconnection took advantage of the layered structure of their digital services and protocols. Indeed, this approach led to the conceptualization of both the Open System Interconnection (OSI) standard and the TCP/IP model, instrumental to the consequent shaping of Digital Internet. The underlying idea about layering is that services provided by each layer add value to the set of lower layers in a manner that ensures the highest layer receives the necessary services for running distributed applications. According to authors, the layered structure makes it available a framework to divide an elaborated and complex service/task in more manageable tasks and, on top of this, the framework earns flexibility and ability to keep delivering services in an efficient way when disruption strikes one service layer.

Being the logistics networks highly fragmented and based mostly on proprietary networks and assets, the concept of Physical Internet arose with the intent to interconnect logistics services on a worldwide scale exploiting the comparison with the well succeed digital network. Starting from the Digital Internet experience, authors propose in this paper a seven-layer Open Logistic Interconnection (OLI) model able to outline how logistic services could be arranged within and across these layers.

Open Logistic Interconnection Model

While digital networks primarily deal with data, logistics networks are characterized by their heterogeneity and the additional feature of managing not just goods, but also a significant amount of information, some of which is already partially digitized, as well as money, fortunately more and more digitalized nowadays. Achieving seamless universal interconnectivity within this intricate context necessitates the adoption of a standardized approach, similar to what was accomplished with the Digital Internet. Consequently, an Open Logistics Interconnection Model of the Physical Internet is outlined.

In the OLI model, a layer comprises a group of conceptually similar functions that offer services to the layer above it while receiving services from the layer below it. These services, provided by various entities, including software agents, automations, equipment, and even humans (either directly or through software interfaces), are described below with a peculiar focus on data and information exchange between layers, pi-actors, pi-constituent. As far as info exchanges are concerned, they can happen vertically between different level layers within the same actor and horizontally between same level layers and different actors. Each of these data/services flows is managed by standardized and well-structured protocols as we can see from figure 5.

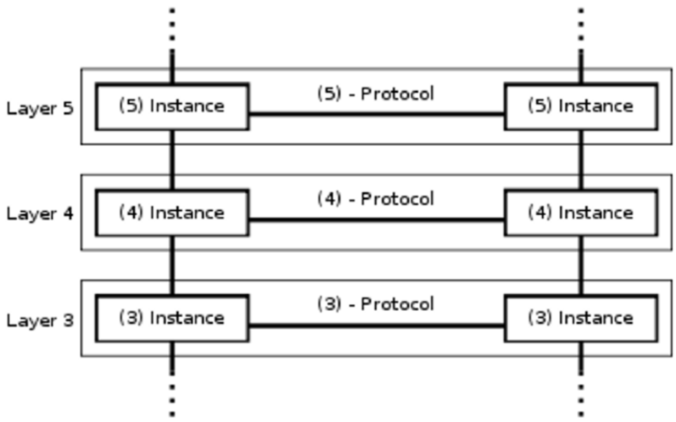

Figure 5 Services description of OSI model by Montreuil, Ballot, & Fontane, 2012

The OLI model proposed by this paper is founded on the following seven layers: (1) physical, (2) link, (3) network, (4) routing, (5) shipping, (6) encapsulation, and (7) Logistics Web.

- *Physical Layer*: The Physical Layer, having in input all loading, moving, sorting, storing, retrieving, and unloading orders from the upper layer (Link Layer), manages physically all pi-constituent able to carry out orders and commissions. Therefore, it is in charge of physically encapsulate freight in the available modularized and standardized pi-containers according to size, weight, freight-integrity preservation requirements and other attributes of the good to ship that can trigger a special treatment (physical internet entry and exit gateways – containerization/de-containerization). Physical layer, received triple-assignment of pi-containers to pi-means to pi-links and composition/decomposition orders (from Network Layer via

Link Layer), takes care of loading, unloading, moving within nodes and between nodes, physical check at nodes' gateways (entry/exit), sorting and storing activities involving pi-containers, pi-vehicles, pi-carriers, pi-conveyors etc (Montreuil, Meller, & Ballot, 2010).

Furthermore, the activity of validations and verification of physical elements operating in the network is among its duties and it is aimed at detecting faults and the pi-constituents are able to carry out demanded tasks (for ex: physical and functional integrity of pi-containers according to shipping requirements and pi-means or consistency of client agreement with service being provided). In case of defects detection, reaction and maintenance is expected to ensure that processes do not slow down or provide inferior quality of service.

Since this new logistic paradigm needs standardization of physical interfaces and physical specification of pi-constituent, here service providers and beneficiaries define, for example, structural and hardware as well as dimensional and functional specification of pi-containers and pi-entities (gripping mechanisms, interlocking mechanisms, layouts, and positioning of entry and exit gateways of pi-nodes and of entire networks).

This layer gives back to upper layer (Link Layer) information about pi-constituents status included defect monitoring insights and move order tracking. To this purpose, technologies like RFID can be used to digitally transpose physical status/activities.

- *Link Layer*: The Link Layer is primarily concerned with identifying and potentially rectifying unforeseen events that arise from activities at the physical layer. It achieves this by verifying the coherence between physical operations (in input from lower layer) and their digital representation, thereby ensuring consistency. Whenever coherence is not guaranteed and dysfunctions are detected, it engages in activities aimed at reactivating the usual functioning. Some examples of dysfunction managed here are road segment congested or totally unusable, out-of-order pi-conveyors, lost pi-containers or disrespected shipment requirements along the chain or security tracking system not responding appropriately to tracking and trace needs.

  Furthermore, this layer is in charge of ensuring and managing correct and compliant hand-over of pi-containers from a pi-actor to another one avoiding error propagation, for example, making sure that the triple-assignments of pi-containers to pi-means to pi-links are respected according to routes computed in layers above (Routing Layer) and pi-constituents' status. For example, here service suppliers like nodes make sure that pi-links, with its monitored traffic level, assigned to specific pi-means are coherent with time-requirements of every shipping order loaded on. To carry out these activities, the Link Layer validates and monitors each flow link state and route segments in order to inform layers above (Routing, Network Layers) and let them route and reroute pi-containers within networks.

- *Network Layer*: The network layer's primary objective is to address the interconnectivity, integrity, and interoperability requirements of networks within the Physical Internet. It facilitates the necessary functional and procedural mechanisms to ensure that π-containers can be efficiently routed within a π-network and across multiple π-networks, while simultaneously upholding the desired level of service specified by the routing layer. Indeed, this layer deploys protocols aimed at assigning pi-containers to pi-means and finally to pi-links, deemed optimal by routing activities carried out in the above layer (Routing Layer). Besides this, it monitors pi-container flows across PI networks in order to detect route errors and react promptly by minimizing shipping disruption. On the other hand, here intermediate pi-nodes handling specific pi-containers with predefined routes (computed at the start node) can identify specific routing opportunities and respond accordingly to capitalize on them and therefore, conceptually, in the layered structured analysed here, these opportunities can be forwarded to the upper layer (Routing Layer) for rerouting the specific pi-container or consolidated pi-containers along different pi-links.

  Another crucial activity carried out by pi-nodes and conceptually located in the network layer is the composition/decomposition of pi-containers. Once the pi-containers arrive at a node and are eventually unloaded from the pi-truck/train and have to be reloaded onto another vehicle, in order to have an optimal and efficient utilization of pi-means the PI precepts require containers to be composed and decomposed among themselves (thanks to interlocking and gripping mechanisms) according to several factors (same destinations, same 3PL companies, same environmental requirements etc). Given a substantial computational capacity of pi-nodes system, pi-container composition can be further optimized considering future states of different pi-containers (next nodes in the route and future shipping disturbances and needs) in order to minimize unloading/recompositing/loading activities.

- *Routing Layer*: The routing layer makes functional and procedural means available for managing efficiently the routing of a set of pi-containers from its start node to its destination node. Indeed, here pi-nodes provides routing services to compute optimal paths for pi-containers according to shipping contracts (destinations, time attributes, priority specifications etc), network state (monitored by Network Layer), route segment status exploiting well-structured protocols. Another input from lower layers to Routing Layer services are pi-means status, service capability, capacity and performance that are monitored and processed by pi-nodes in order to compute efficiently routes within each network and across networks.

- *Shipping Layer*: The shipping layer facilitates the efficient and dependable transportation of sets of π-containers from shippers to their intended recipients. It offers the necessary functional and procedural tools to enable smooth and reliable shipping operations. These sets of containers could represent orders. Indeed, here shipping services providers take care of setting, managing, and closing the shipment between the shipper and each recipient. They receive pi-containers and shipment requirements (shipment requests) from upper layers, creates an instance of shipment that will be monitored throughout all the life cycle of shipment and requires transport services from lower layers. These services providers can be 3PL providers, operating in the market of container shipping, on which clients rely as for the shipping management. In this layer, the type of service to deliver is defined (shipment is managed accordingly) and the receipt acknowledgement is managed too.
- *Encapsulation Layer (Deployment Layer)*. Despite the fact that Physical Layer deals with physical encapsulation of freight in appropriate pi-containers, it is the Encapsulation Layer that provides means for efficiently encapsulates product to ship in uniquely identified (unique ID) pi-containers before accessing PI networks (at PI entry gateways).

  The layer keeps track of and verifies the abilities, capacities, prices, and performances of π-nodes and π-means. It also monitors the overall performance of π-service providers, making it available to everyone in the network, and provides updates on the status of signed contracts and deployed π-containers.

  From this layer, anytime a freight is encapsulated, a shipment request is sent to the Shipping Layer with information like number and types of pi-containers, assignment between products and containers, type of service (express, normal etc).
- *Logistics Web Layer*: The Logistics Web layer acts as a bridge between the Physical Internet and logistics service users. It offers functional and procedural tools that empower users to utilize the Physical Internet effectively. This includes making

dynamic decisions regarding product supply, production, distribution, and transportation. All of these actions are facilitated through an open and global Logistics Web. In this layer, PI clients and service providers (one actor can be both) express needs, programs flow of pi-means, products, services and establishes supply contracts.

Each actor, allowed to do it, here can monitors contracts, stocks, flows, service provider capabilities, performances through the efficient informational synchronization with the Encapsulation Layer. For example, who requested a shipping service can monitor the shipment, have visibility of tracking info, and assess compliance to contract agreements. All these activities and visibility would be enabled by current software for supply chain management, logistics management, operations management, and enterprise resource management.

In addition to the inter-layer service logic, logistics services are also organized among actors within each layer. For example, in the lowest physical layer, services focus on ensuring the proper physical and digital loading of π-containers into trailers. In the highest layers, services handle the physical, digital, and operational coordination required for defining and coordinating segments, routes, and shipments.

These service layers come into play within every user of the Physical Internet and within each logistics service provider. They are implemented across all nodes in the network to ensure efficient, robust, and sustainable source-to-destination delivery, routing, deployment, and monitoring of π-containers within the Physical Internet.

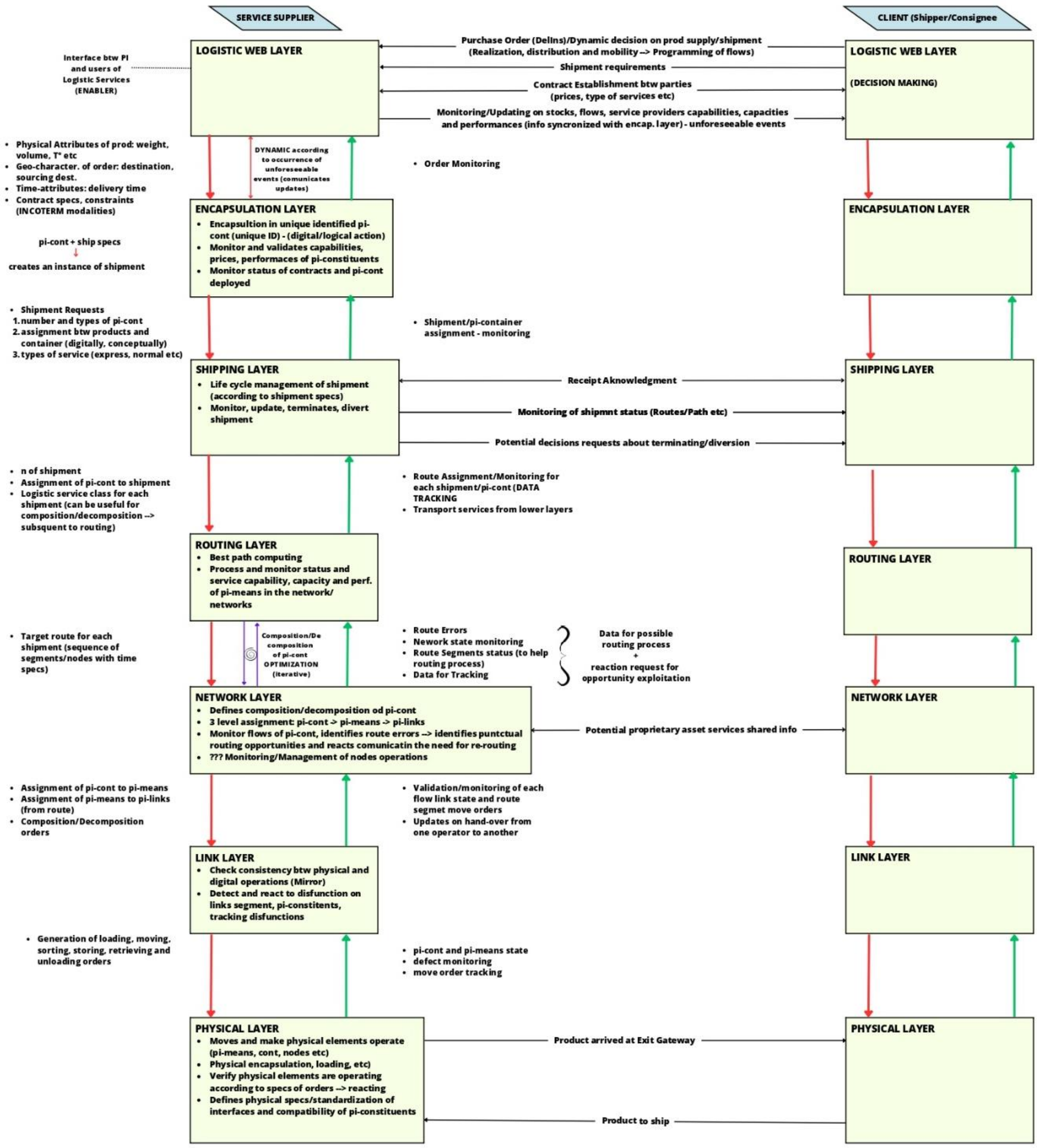

Figure 6 OLI model inter-layer protocols description by Montreuil, Ballot, & Fontane, 2012

Analogies between internet network and logistics service networks - challenges involved in the Interconnection - Sarraj, Rochdi, Ballot, Eric, Pan, Shenle, Montreuil, Benoit – 2012

While the logistics network supporting the supply chain continues to be characterized by its heterogeneity and is poorly interconnected, the computer network in the past decades has managed to overcome this obstacle with the arrival of the Internet. Building on this observation, the authors in this paper set out to explore the similarities between the digital internet and the logistics service network by attempting to outline an interconnection architecture for the new logistics paradigm of interest for this thesis, namely the physical internet.

Nowadays, all logistic services are provided within a series of networks evolving autonomously as for business models, design of service, trucks, packages, dedicated warehouses etc. Despite this, the various independent networks share infrastructures like roads and railways. However, the autonomy of logistic networks proved to be inefficient since all actors and little networks tend to excessively rely on dedicated resources without service providers exploiting potential synergies empowered by interconnection. Therefore, the paper tries to demonstrate strong similarities between Digital and Physical Internet leveraging on three main characteristics: interconnection of networks, structure of the network of networks and routing of objects across networks.

The autonomy of logistics networks, with organizations relying on dedicated resources, creates inefficiency. Service providers aim to enhance operations but struggle due to a fragmented market and conflicting customer demands. This independence leads to overuse of resources. Providers, though capable of improving logistics, face challenges in finding synergies among a limited number of conflicting customers in a fragmented market.

This paper examines analogies between computer networks, particularly the Internet, and logistics service networks. The analogy is articulated through three primary characteristics: network interconnection, the structure of network systems, and object routing across networks. Despite the fundamental importance of all three topics just named, we will focus mainly on the structure of network of networks, merely summarizing the other two major challenges of the physical Internet. This research decision stems from the interesting insights that the paper provides about networks authority (and service providers relationships) and relative Physical Internet architecture exploiting Digital Internet fractal structure.

Interconnection of Logistic networks

Leveraging on the analogy between Digital and Physical Internet, authors transpose the concept of universal interconnection of network to PI. According to this view, a shipper utilizes a nearby node as an intermediary to handle, store, and dispatch their merchandise to the final destination using various available logistics options. Similar to how data is encapsulated in standardized packets in the realm of the Internet, goods are packaged in standardized, modular, intelligent, and environmentally friendly containers referred to as π-containers. Logistics networks can interconnect by establishing new transport services between nodes of different networks. Shippers can transmit π-containers to hubs in other networks, and nodes can send π-containers to nodes in different networks. This way of interconnecting networks already exists in the form of traffic sharing agreements. In spite of the fact that logistics networks exploit already this way of interconnection, no global standardization leads to poor results in terms of efficiency.

Architecture of PI Network of Networks (at levels) – communication architecture at different levels

Taking into consideration the current logistics paradigm and the peculiar roles played by organizations, authors provide an enlightening transposition between architectural elements of Digital Internet and Physical Internet. Before explaining the architecture of the Physical Internet proposed by this paper, it is necessary to give a clarification about the architecture on which authors base the analogy, namely the one of Digital Internet.

The Digital Internet exhibits a fractal structure, where the highest hierarchical level comprises a collection of interconnected networks referred to as "Autonomous Systems" (AS). These were introduced to address the decentralized nature of the Digital Internet, which lacks a single controlling authority. Each AS is autonomously managed by a single operator, typically representing a large public or private entity. Communication between distinct AS is facilitated by specialized routers known as "border routers", utilizing specific protocols. Within an AS, data is routed internally by "internal routers," and internal communication occurs using other types of protocols (Tanenbaum, 2003) (Huitema, 1999) (Hardy, Malléus, & Méreur, 2002).

The connections between different AS are based on functionality, allowing for the possibility of geographically overlapping AS that operate simultaneously in the same area. Furthermore, each autonomous system comprises additional networks referred to as "zones" or "areas." These zones can be considered as sub-networks, with or without their own management protocols. This hierarchical decomposition can be further extended to a third level, involving sub-networks within sub-networks, and so on, until reaching the local network or an individual host (Hardy, Malléus, & Méreur, 2002).

Starting from this, authors provide a three-level architecture (further extensible) for Physical Internet that below we summarize top-down:

1. **Inter-networks level:** at the top of this architecture this paper poses protocols and structures enabling for the sharing of containerized logistic services among different

networks (if required). This implies different networks, managed by different actors (AS) to communicate, and collaborate to deliveries/services. This inter-operations/coordination may be managed by shared/globally agreed PI protocols – highest hierarchical protocols at foundation of the PI. In this new architectural paradigm "border nodes", akin to common national/international exchange platforms (international airports, ports, train stations), or specific nodes may be able to interconnect two heterogeneous logistical networks, each managed by a PI autonomous logistic system with specific administrative authority. Since the authors do not place any constraints on this, PI AS can geographically overlap or rely on an exclusive territory.

2. **Network level:** each network is defined as a set of logistics services managed by one and only one actor (service provider, producer or express carrier, international third-party logistics provider 3PL). In this context, it kicks in the Physical Internet Autonomous Logistic Network. It consists, on its highest hierarchical level, of a large network interconnected to all others (by border nodes), each independently managed by a single operator as said. This network may have not geographical meaning but given the heterogeneity in the transport means and regulations paradigm in different countries/regions, the AS of competence has to manage this heterogeneity when its network crosses national borders. Therefore, it has to manage protocols to interact within the same AS Zone of Sovereignty, and among different AS authorities (often different protocols from AS to AS)

3. **Intranetwork Service Provider (Level):** at the lower levels there are all logistics service providers managing sub-networks (Areas, zones), local networks, hubs/nodes (internal nodes). Logistic Service Providers provide access to an interconnected network (Hubs, Transits, Nodes within a network managed by AS). They can be property of AS of competence or of service providers different from AS that has to stick to AS protocols to communicate with other sub-networks within the network and rely on border nodes to make pi-containers cross zones of sovereignty at which they belong to.

By employing this architecture, the Physical Internet facilitates a fractal interconnection among numerous logistics networks. These networks can include existing networks operated by logistic service providers, which currently serve exclusively their own clients but have the potential to be open to clients of other service providers. Additionally, these networks can also encompass newly designed and implemented networks that aim to enhance the implementation, adoption, and expansion of the Physical Internet concept.

In this section, authors tried to present a potential framework for the Physical Internet aiming to establish connectivity between different logistic services and enable efficient and sustainable routing of pi-containers.

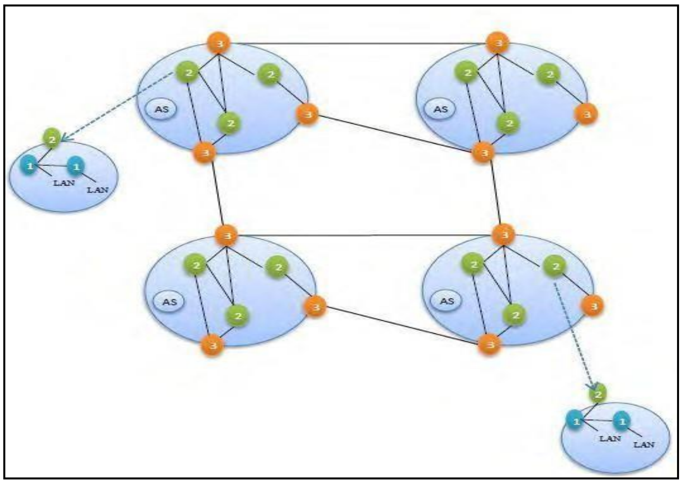

Figure 7 Internet concept map explicating the hierarchical nature of the interconnected networks (Sarraj, Ballot, Pan, & Montreuil, 2012). 3: Border Nodes of the AS (level 3); 2: Border Nodes of the AS (level 2); 1: Internal Nodes of the AS (level 1)

Routing Operation

The organization of routers in the Digital Internet involves determining the direction for each datagram based on routing tables. These tables provide the next router for the datagram based on its destination, following predefined criteria. In the Physical Internet, a similar concept can be applied using routing tables at each node (e.g., π-hub) to determine the best next node for π-containers based on criteria such as cost, delivery time, and CO2 emissions. However, the analogy between routers in the Digital Internet and nodes in the Physical Internet has limitations as the logistic function of π-hubs encompasses more than just routing. The Physical Internet should consider logistics needs like managing transport capacities and sorting in π-hubs. Unlike the Digital Internet, the Physical Internet can utilize flow understanding and future state estimation to optimize routing protocols between nodes. This possibility, lead us to think about an information exchange infrastructure able to gather information about past and current network status in order to make nodes able to process those data and provide future state-informed routes. This would involve data about road congestion patterns, nodes capabilities, performances and availability to receive and handle pi-containers, pi-carriers performances and availability to take charge of specific pi-containers as well as pi-containers info propaedeutically to consolidation/deconsolidation activities (exploiting interlocking mechanisms to consolidate multiple pi-containers among themselves).

Functional Design of Physical Internet Facilities A Road-Based Crossdocking Hub - Montreuil, Meller, Thivierge, Montreuil - 2012

This paper is part of a three-paper series presented at the 2012 IMHRC, which focus on providing functional designs for three Physical Internet (PI) facilities. Specifically, this paper concentrates on a unimodal road-based crossdocking hub, specifically designed to leverage the advantages of modular containers within the Physical Internet framework. The hub aims to facilitate efficient and sustainable transhipment, ensuring smooth movement of goods from inbound trucks to outbound trucks (K.R., 1999) (Vis & Roodbergen, 2008). Authors propose a detailed and feasible design for such a facility outlining methods to measure its performance and to enable hubs to acquire necessary data and to send it to actors interacting with it. Given the fine-graned description, in the context of this thesis we analysed it focusing on the exchange of data and information (protocols) aimed at facilitating PI activities in hubs.

We firstly discuss in general terms the properties of a pi-hub devoted to physical internet in the next section and then we will report insights on the detailed design provided by authors in this paper.

Road-Based Crossdocking Hub

The main objective of a road-based crossdocking π-hub is to ensure the efficient transfer of π-containers from inbound trucks to outbound trucks, enabling the smooth transfer of each container within the designated time window across the network of π-nodes. Π-hubs play a critical role in the effective functioning of the Physical Internet by specifically handling smart, modular, and standardized π-containers, facilitating seamless movement within the network. Equipped with specialized π-transporters, these hubs ensure efficient loading, transportation, and unloading of the π-containers. While crossdocking π-hubs are generally accessible to certified users within the Physical Internet, there may be restrictions on the types of π-containers authorized for handling at each hub.

At the start of the trip, all π-containers originate from a specific location and must be delivered to their assigned destination within a predetermined delivery time window. Although the pickup at the origin location may or may not be part of the Physical Internet, at some point, the π-container entering the Physical Internet must be explicitly processed at a π-hub (starting pi-node). Similarly, upon reaching the destination location, the container is transferred to a transporter at a final π-hub for the last-mile delivery. These two π-hub nodes serve as π-gateways, marking the origin and destination of the load within the Physical Internet.

Processes And Info/Data Exchange

Processes before truck enter the pi-hub

When a driver-truck pair (or driver-truck-trailer) indicates their intention to visit a π-hub, whether empty or carrying π-containers to tranship or not, a series of negotiation/routing protocols come into play. These protocols determine the following:

- The next truck assigned to the driver, specifying the departure time and destination.

- If it is the case, the next trailer assigned to the truck.

- The set of π-containers to be loaded onto the trailer or truck.

- The subsequent destination for each π-container to be transhipped, along with the specific trailer or truck on which it should be loaded.

Negotiation between actors interacting with pi-hubs and the same pi-hubs will be based on some pi-hub KPI's. For the drivers, trucks, trailers and π-containers, it is important to know what is the average time spent in the hub, which is the sum of the time spent waiting at the gates, being processed at the gates, waiting to unload, unloading, waiting for readiness of the set of π-containers to be loaded, loading the π-containers on the appropriate carrier, then waiting to depart. Authors combines them into the "hub time" from the three perspectives (trucks, trailers, and π-containers) and the "gate time" (waiting at the gates, being processed at the gates, and then waiting to depart). This paper provides the following specific KPI's: average and maximum throughput time (π-containers, trucks, trailers, drivers), average capacity utilization of departing carriers (trucks, trailers), average percentage departing in preferred direction (π-containers, trucks, trailers, drivers), average percentage expedited assignments (π-containers, trailers).

Prior to getting to the π-hub, π-system asks to the driver some procedure's questions delivered to and answered from truck's multidisciplinary dashboard computer. Some questions are related to the driver status and needs. Other questions are about validating from where it comes and where is its intended next destination(s) (if any). The π-system extracts autonomously data about all loaded π-containers and their pertinent logistics information. The π-system has also communicated with its equivalent at the source π-hub where the truck comes from and got the equivalent information for cross validation and advanced scheduling purposes.

When the truck is quite near the π-hub, the π-system communicates to the driver the specific π-InGate he has to pass through to enter the π-hub. The truck enters into the site by the dispatched π-InGate and all the on-site identification and scanning processes begin. After this, the π-system analyses its database to give an efficient work order to the driver, according to the π-hub site and facility status. Π-system has to organise and plan the exchange of π-containers matches of the π-hub from one carrier to another. A detailed path and task description is shown on the truck's computer.

Processes while the truck is in the pi-hub

The carriers holding a combination of π-containers with various destinations are considered as arriving carriers, while carriers departing from the π-hub must transport π-containers destined for the same next location. As the truck arrives at the appropriate dock for unloading, the π-system continuously optimizes the allocation of trucks to the π-ingates, π-Outgates, π-buffers, and π-docks.

Once the next destination for a truck/trailer has been determined, all π-containers on board that are not intended for the next destination must be unloaded. Subsequently, a reconfiguration process takes place to facilitate the overall crossdocking operations at the current and subsequent π-hubs. This process involves rearranging the remaining π-containers on the truck/trailer, grouping them according to their unloading destinations and leaving enough space between groups to accommodate the next set of π-containers to be loaded.

After unloading from their inbound carriers, the π-containers enter a preparation process, where they are organized according to common destination, available space on trucks or trailers, specific spatial requirements, shared ownership, and unloading destinations. The π-containers are then prepared to be loaded onto their next carrier. The π-system manages these processes, orchestrating the movement of π-containers within the π-crossdock and updating the database accordingly.

The loading process mirrors the unloading process, ensuring that the appropriate groups of π-containers are loaded onto the carrier. Similarly, the departure process mirrors the arrival process. Upon departure, the driver, truck/trailer, and its π-containers are registered, verified, and scanned to ensure routing integrity and security measures.

Acquisition/Exchange/Process Data Enabler

In this section, we describe, according to authors design proposal, the technological devices and systems enabling data acquisition, exchange and processing and which data they hold and exchange.

π-system enabling data exchange within the hub and across pi-actors

The π-system serves as a crucial tool for managing and coordinating the activities of different equipment within the π-hub. This includes overseeing validation gates, barriers, truck's multidisciplinary dashboard computers, as well as x-ray inspection. Additionally, the π-system functions as a platform for electronically transmitting work orders to truck computers and efficiently managing all processes related to the exchange of π-containers within the π-hub.

Truck's multidisciplinary dashboard computer

The truck's multidisciplinary computers are typically positioned in the truck's dashboard and serve as a crucial communication interface between the driver and the π-system. These computers are specifically designed to meet the standards and protocols of the Physical Internet, enabling seamless interaction with the π-system. In addition to their communication capabilities, these connected computers also function as GPS devices. Leveraging the power of the Physical Internet's real-time database and historical statistics, the computer can exploit route opportunities voiding traffic congestion, construction zones, and other potential causes of delay.

The truck's multidisciplinary dashboard computer gathers the following information: its unique identification number, the unique identification number of the current driver of the truck, the unique identification number of the trailer attached to the truck, the unique identification number of every π-container it carries, the serial number of the truck, the registration number of the truck, insurance number related to the truck, the last thorough check of the truck and the dates for future checkups, GPS positioning, an interactive and detailed map of all π-nodes to visit, the historic list of the π-nodes visited and planned to be visited, the number of driving hours remaining in the day for the driver in the truck, the work order history and planning, important documents and messages to drivers.

Smart tag identification for road-based trailer

Smart tags are used to gather information about their owner. These smart tags are used to collect and update information on the trailer and the π-containers it carries. They mainly contain information on the *trailer* (the unique trailer's identification number, the registration number of the trailer, identification number of the agent in charge of the logistics equipment, the last full and thorough equipment status audit, the serial number of the equipment, specific dimensions and features of the equipment, historic movement of the equipment for better traceability) and on the *carried π-containers* (unique identification number of all π-containers carried ,the full list of delivery items inside all the π-containers, the precise location of goods inside all the π-containers, maintenance information and particular terms of the commodities, the unique identification number of the owner(s) of the commodities, the exact addresses of final destination and origin of all the π-containers, the expected entire path of each π-container, historic movement of the π-containers for better traceability).

X-ray and radiation detection inspection system

X-ray inspection systems at π-ingates and π-outgates scan vehicles, trailers, and π-containers generating high-resolution colour images. These images are transmitted to the π-system database for validation and future comparisons. For subsequent inspections, the π-system compares newly created three-dimensional images with archived images. If they are identical, the equipment is considered compliant. The x-ray security system plays a critical role in maintaining conformity and enhancing security within the Physical Internet.

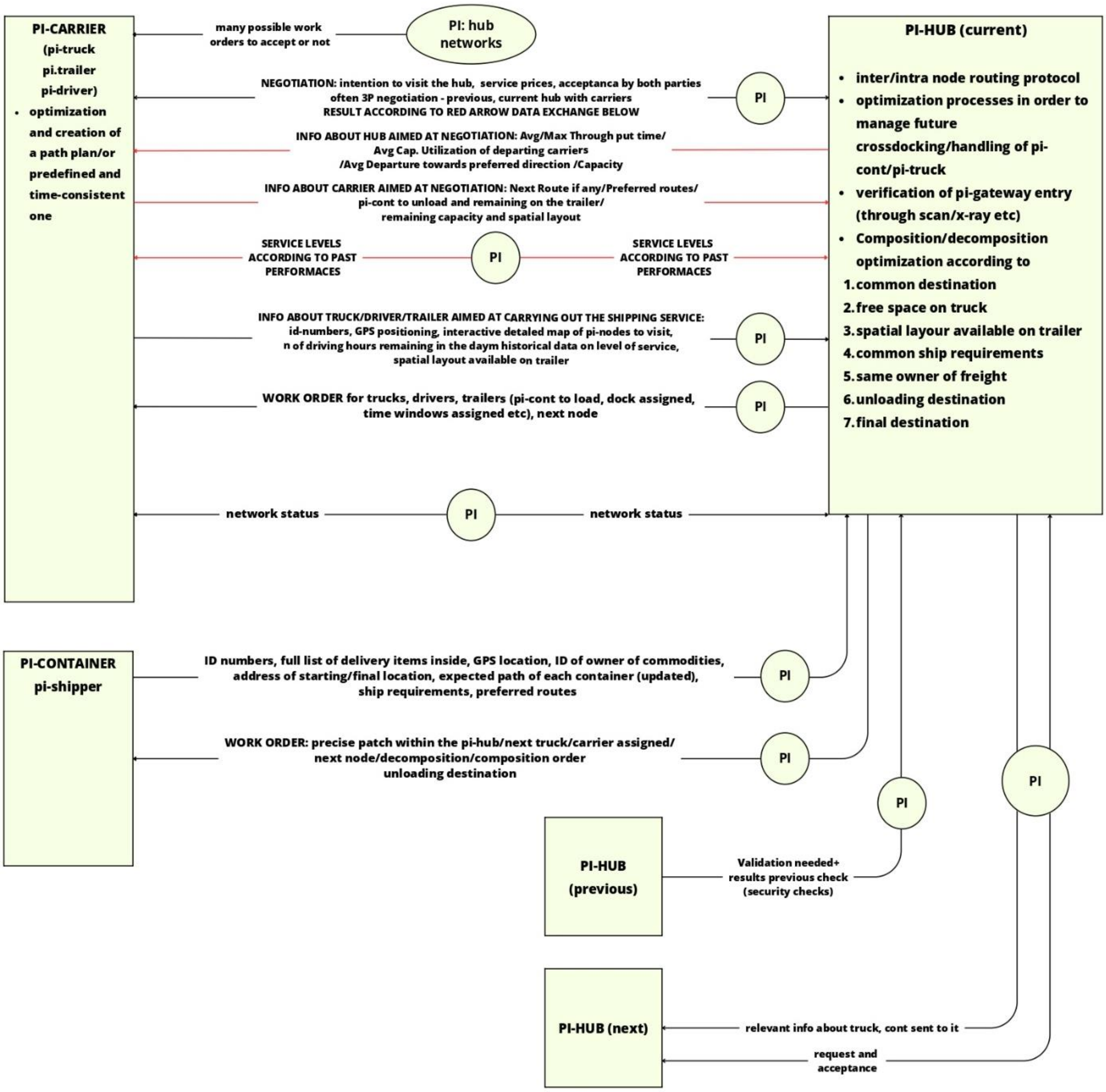

Figure 8 Protocols inferred from Sarraj, Ballot, Pan, & Montreuil (2012) – circles refer to an unspecified shared data structure

Functional Design of Physical Internet Facilities A Road-Based Transit Center - Meller, Montreuil, Thivierge, Montreuil – 2012

The focus of this paper is on a road-based transit center, known as a road-based π-transit. The main purpose of a π-transit node, according to PI literature, is to facilitate the transfer of π-carriers from their inbound to outbound destinations. In this case, a road-based π-transit enables the transfer of π-trailers from one truck to another.

The objective of the paper is to provide a feasible design that aligns with the mission of this type of facility. The design aims to ensure smooth and efficient transfer operations at the road-based π-transit. Additionally, the paper identifies methods to measure the performance of the design, allowing for evaluation and continuous improvement. It also explores research models that can assist in the design process, providing valuable insights and guidance.

We firstly discuss in general terms the properties of a pi-hub devoted to physical internet in the next section and then we will report insights on the detailed design provided by authors in this paper. For more detailed description of data exchange design refer to the paper "Functional Design of Physical Internet Facilities A Road-Based Crossdocking Hub" by Montreuil et. Al., still part of the three-paper series.

Road-Based Pi Transit Center

The primary mission of a road-based π-transit center, also known as a PI transit center, is to ensure the efficient and sustainable transfer of trailers from one truck to another. This serves two main purposes: firstly, to enable trailers to reach their intended destinations within the designated delivery time window, and secondly, to assist drivers in reaching their target destinations by the end of their workday.

To fulfill this mission, certain key information is required as part of the PI operating protocol. Trailers originate from specific locations and must be delivered to their destinations within the delivery time window. Although the pickup at the origin location may or may not be part of the PI, at some point, the load enters the PI, and during delivery, it will pass through a π-transit center. These transit centers act as gateways within the PI, marking the origin and destination of the load.

In addition, each driver in the PI has a limited number of available working hours determined by hours of service regulations and individual requirements. Furthermore, drivers have a target destination they aim to reach by the end of their workday.

By considering these factors, road-based π-transit centers play a vital role in facilitating the smooth movement of trailers within the PI framework. They contribute to timely deliveries, efficient route planning for drivers, and overall operational effectiveness. Understanding the mission and incorporating these fundamental elements into the PI operating protocol is crucial for the successful functioning of road-based π-transit centers and the broader Physical Internet system.

Processes And Info/Data Exchange

When a trailer-driver pair signals its intention to visit a π-transit node, a negotiation protocol determines to which driver the trailer will be assigned to move it towards its PI-destination as well as to which trailer the driver will be assigned to move him/her towards his/her end-of-shift destination. One key performance indicators (KPIs) driving negotiation and intention of pi-carriers to visit that pi-transit is certainly the average time spent in the transit center, encompassing waiting, processing, unhooking, matching, and hooking times. This is referred to as the "switch time" and "gate time" from both the truck and trailer viewpoints. Additional KPI of interest include the percentage of time a driver is assigned a trailer going in their preferred direction (the one the driver wants to undertake to go back home).

A truck, with or without a trailer, enters the π-Transit from the π-Road. The π-Transit operates based on a timetable managed by the π-System, booking specific π-Switch bays within a given time frame. To enter the π-Transit, trucks must request access from the π-System, which analyzes the request, provides an access code, and reserves a bay in the π-Switch if necessary. The π-System tracks the movement of vehicles in real time, ensuring efficient management of trucks, trailers, and facilities within the Physical Internet network.

Upon arrival at the π-InGate, trucks pass through one of the four security gates. Depending on the π-System's request or transportation needs, the truck undergoes a rapid or deep security scan. Deep scans involve X-ray and radiation detection systems to identify illegal or hazardous goods. Security gates read or update information from the driver identification smart card and trailer smart card, which are compared with the π-System's database. If everything matches, the π-System transfers a work order to the truck's dashboard computer, assigning specific tasks and locations within the π-Transit.

Once the driver confirms receipt and understanding of the work order, a barrier opens, allowing the truck to enter the designated π-Aisle. The driver follows the provided work order to complete the tasks within the π-Transit within a specific time frame. The π-System's algorithms consider contingencies, needs, and capacities to optimize traffic flow and minimize wasted time.

Once the pi-Truck with a Pi-Trailer reaches the right switch bay, they are decoupled according to work order provided by pi-system. Consequently, each pi-Truck reaches the switch bay where to pick-up the next trailer to transfer to the next node on schedule, if any. Otherwise, it will head towards the pi-transit outgate. Once the pi-truck is coupled with the new trailer, it will reach the pi-transit outgate for last scan and security check.

Overall, the π-Transit operates as a controlled and monitored facility, ensuring the efficient transfer and management of trucks and trailers within the Physical Internet network. The integration of security measures, work orders, and real-time tracking through the π-System enhances interconnectivity and in turn performance and operational effectiveness.

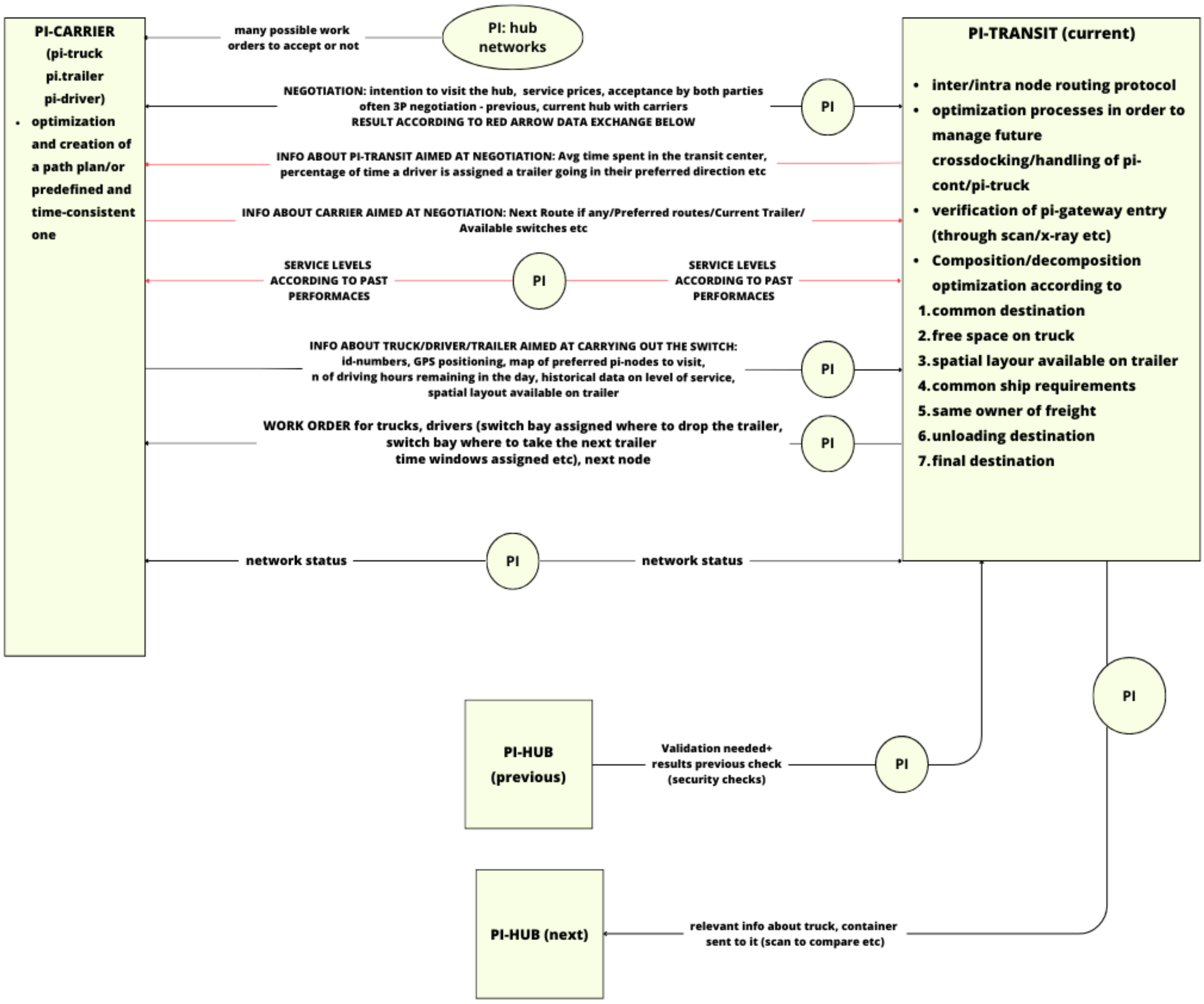

Figure 9 Protocols inferred from (Meller R. D., Montreuil, Thivierge, & Montrueil, 2012) – circles refer to an unspecified shared data structure

Functional Design of Physical Internet Facilities Road-Rail Hub - Ballot, Montreuil, Thivierge – 2013

This paper is part of a series focusing on functional designs for Physical Internet (PI) facilities. Specifically, it presents a design for a PI road-rail hub that facilitates the transfer of PI containers between inbound and outbound destinations, involving trains and trucks. The objective is to provide a feasible design that meets the facility's objectives, including performance measurement and identification of research models for future design.

We firstly discuss in general terms the properties of a pi-hub devoted to physical internet in the next section and then we will report insights on the detailed design provided by authors in this paper.

Road-Rail Crossdocking Hub

The mission of a road-rail π-hub is multifaceted. Firstly, it involves receiving trucks and handling their inbound π-containers, ensuring timely loading onto assigned trains for transportation to the next rail-based π-node. Secondly, it entails receiving trains and handling their inbound π-containers, either loading them onto trucks or subsequent trains for onward movement to the next π-node or final destination. Thirdly, the hub is responsible for handling and sorting π-containers in coordination with trucks or trains. These missions rely on essential information within the PI operating protocol, including delivery time windows and the ability to redirect volumes between road transit centers and the hub (Ballot, Glardon, & Montreuil, OpenFret: Contribution to the Conceptualization and Implementation of a Road-Rail Hub for the Physical Internet, 2010). Lastly, the hub performs sorting operations for π-containers transitioning between train services and connecting with another train.

Processes And Info/Data Exchange

Road to train or from train centric flows

When a truck, with a flat bed or pulling a trailer, presents itself at the PI Road-In Gate it is insured that the truck, the trailer when pertinent, its current and assigned PI containers are registered and expected in the planned time window. PI Road-In Gate proceeds with a security check. At the entry gateway, x-ray, and radiation detection inspection system procede with weight checking, coding identification, temperature, validation of electronic seals, consistency check with data forwarded by previous nodes about trailers, pi-containers, drivers and so on. The process carried out at PI Road-In Gate allows to associate a driver's license to an actual driver, an operator and a truck, and to associate the truck with a set of PI containers and a trailer when pertinent. After this, the π-system analyzes its database to give an efficient work order to the driver, according to the π-hub site and facility status. Π-system has to organise and plan the exchange of π-containers matches of the π-hub from one carrier to another (in case of truck-train or train-truck transhipment). A detailed path and task description is shown on the truck's computer.

A system has to optimize the allocation of inbound PI Bridge docks to trucks so as to minimize their movement through the PI hub and to ensure that their PI containers reach their position beside their assigned railcar location in timely and orderly fashion with minimal overall PI container movement and congestion.

After unloading from their inbound carriers, the π-containers enter a preparation process, where they are organized according to common destination, available space on trailers or train wagons, specific spatial requirements, shared ownership, and unloading destinations. The π-containers are then prepared to be loaded onto their next carrier. The π-system manages these processes, orchestrating the movement of π-containers within the π-crossdock and updating the database accordingly.

The loading process mirrors the unloading process, ensuring that the appropriate groups of π-containers are loaded onto the carrier. Similarly, the departure process mirrors the arrival process. Upon departure, the truck/train, and its π-containers are registered, verified, and scanned to ensure routing integrity and security measures.

In parallel to the road-based operations, rail-based operations are performed.

Train centric flows

A train arrives at the PI Rail-In Gate. At the previous hub, this train has been maximally loaded within its capacity, leaving remaining PI containers to be either reported to a next train or transferred to road travel. The PI Rail-In Gate may scan all PI containers and verify them relative to the train's manifest. Minimally, a sensor reading is performed so as to identify and to locate the train drivers, the train, the set of railcars, set of PI containers, validating their position within the train's railcars, and aiming to avoid handling errors. It enables the validation of the unloading and loading plans to be realized.

Once the train has stopped, pick-and-place type robots grab PI containers having to be unloaded at this PI hub, so as to perform the unloading operation. Such unloading operations can be performed in parallel on all railcars parked along the PI Conveyor.

Once all its railcars have been unloaded and re-loaded as prescribed, the train moves into the PI Rail-OutGate. First a final checking is performed. Once granted permission to leave, the train moves forward out of the PI hub onto the railway.

KPIs of Design

From the Customer's Perspective

Authors take into consideration three customer perspectives crucial in a road-rail π-hub context: the transportation service provider (represented by the truck and driver), the train operator, and the shipper (represented by the π-container). While this paper focuses on the train side of operations, we refer to the other papers of this three-series that conver the truck side.

From the train operator's perspective, it is crucial to understand the time spent at the road-rail π-hub in order to schedule their route and activities efficiently and in turn choose most efficient and profit-trigger pi-nodes to visit. This includes the duration of waiting at the gate, if applicable, as well as the processing time required to unload and load π-containers. Additionally, there is the time spent waiting to join the rail network. Combining all of these times provides an overall measure of the processing time from the hub's perspective. On the other hand, the stop time is more relevant to the rail operator and relates to the overall impact on rail network operations.

Efficiency and optimization are key considerations for the train side of operations. Minimizing processing time and optimizing the allocation of resources such as personnel and equipment are vital to ensure smooth operations at the road-rail π-hub. By reducing processing time, the hub can improve overall throughput and enhance the efficiency of the rail transportation system. Additionally, effective coordination and communication between the train operator, the hub, and other stakeholders are essential to streamline operations and minimize delays. This is the reason for the constant communication and coordination between train operators and hubs.

Understanding and measuring these time metrics allow for performance evaluation and identification of areas for improvement. Research models and performance measurement methodologies can assist in assessing the effectiveness and efficiency of the road-rail π-hub's design and operations. By continuously monitoring and analysing these metrics, the hub can identify bottlenecks, implement corrective measures, and enhance its role as a crucial link in the Physical Internet infrastructure, ensuring seamless movement of goods between different transportation modes.

The main six KPIs identified in this paper are: processing Time (Trains), number of trucks per hour (trucks), empty places on transportation means (trains & trucks), average connections offered (trains), maximum container's transit time (trains to trains, trains to trucks & trucks to trains), average percentage departing in preferred direction (trucks). From the operator's perspective KPI's related to the capacity of the road-rail π-hub are: area of road-rail π-hub, number of railcars processed in parallel per stop, number of π-containers processed in parallel per railcar, number of load and unload bridges for trucks (in and out of the π-hub), number of rows to store and sort π-containers before loading to trains (from trucks and from trains), number of rows to store and sort π-containers after unloading from trains (to trucks and to connecting trains), number of gates (in), number of gates (out), number of parking bays in the buffer (trucks/trailers), average percentage trucks/trailers declined entrance (due to space issues in the π-hub). The KPIs related to the operations of the road-rail π-hub are: number of π-containers handled per period, number of positions used in the π-hub per sector (saturation), number of positions used in the buffer (saturation)

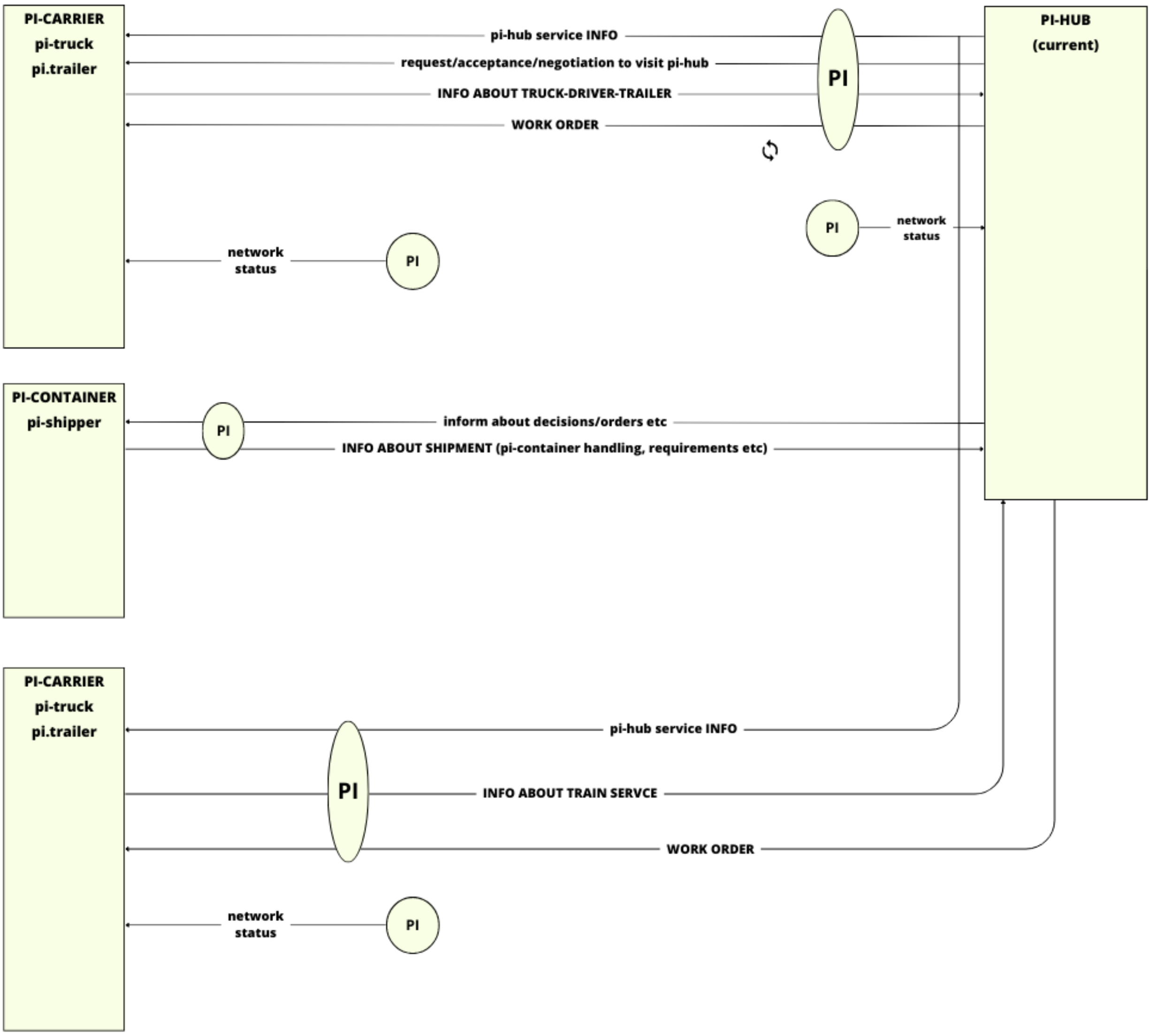

Figure 10 Protocols inferred from (Ballot, Montreuil, & Thivierge, 2012) – circles refer to an unspecified shared data structure

Interconnection logistic networks and protocols simulation-based efficiency assessment – Sarraj, Ballot, Pan, Hakimi, Montreuil – 2014

This paper aims to evaluate the efficiency of a network of networks in the context of an open, interconnected physical Internet. To this purpose, the authors outline a set of transport protocols (rules that would guide different processes within the PI paradigm) to be implemented and then evaluate their performance through a simulation model.

The focus is specifically on protocols involving:

- the loading of pi-containers from orders (freight shipment requests) received from the customer or from shipping service providers (intermediary organizations that request transportation services from the PI network on behalf of the customer)
- routing services that make use of algorithm-based protocols to provide optimal paths for pi-containers from origin to destination via intermediate nodes
- Efficient consolidation of pi-containers in order to optimally fill the transport means at each hub/node before resuming the journey to the next destination

Transportation Protocols

The process of shipping goods within the Physical Internet (PI) differs significantly from current practices and involves multiple steps. Initially, each order goes through the so called “encapsulation” process and therefore is loaded into a "best" fitting PI-container according to shipping requirements (cold chain, size, weight, etc). Once a PI-container is ready for shipping, the optimal path to the destination is determined within the network of available logistics services. This path comprises several segments or logistics services, which could involve trucking to an initial hub, connecting to a train service, and so on until reaching the final destination where the goods are unloaded from the PI-container. Hubs play a crucial role in handling PI-containers during transportation segments.

Upon arrival at a hub, a search is conducted to find the best transportation means for the next segment based on the capabilities, availability, and alignment with the economic, environmental, and time-related objectives of each PI-container. If a suitable transportation service is found, consolidation of PI-containers takes place. However, if a transportation service is unavailable, departure is forced, or an alternate path is computed. Each operation follows predefined rules and optimization methods that call for an intense exchange of information between pi-containers (clients/shipping companies) and pi-nodes, pi-carriers and pi-containers, pi-nodes and other pi-nodes.

Containerisation Of Goods/Encapsulation (Protocol)

The goods containerisation protocol outlines the process of grouping products for shipment within the Physical Internet. It specifies how products are assigned to a single PI-container or a set of PI-containers, determines the appropriate size of PI-container for each shipping group, and establishes the loading sequence and arrangement of goods within each PI-container according to freight characteristics provided by the shipper (size, weight, customer preferences and requirements, time-related issues). The process just explained first presumes the definition of a set of containers, taking advantage of modular dimensions, with accurate optimal sizes, useful interfaces, and functionalities to exploit interconnectivity and info accessibility.

Routing protocol

A routing protocol prescribes how nodes communicate the network state and utilize this information to determine a route between two nodes in the context of Digital Internet. A routing algorithm, based on a cost or distance function (Comer, 2006), is employed to select the most suitable route and in the Physical Internet, authors propose a similar approach to route PI-containers within the PI network.

Just as a data service network in the Digital Internet experiences irregular traffic patterns, a logistics service network also faces similar challenges. However, unlike the fixed capacity of digital internet wires, the transportation industry, particularly trucking, possesses the ability to dynamically adjust capacity according to demand on each route. Additionally, the slower movement of freight compared to information allows for potentially easier traffic anticipation, although this is not always utilized effectively in current practices.

Unlike the Digital Internet, a routing algorithm within a logistics network aims to achieve not only a certain service level but also the optimal utilization of services, such as transportation means, especially those that operate on a scheduled basis. The physical addresses provided by postal systems play a vital role in site location, assuming that well-known warehouses and distribution centers are prepared to receive containers.

As a consequence, authors outline specific properties that PI routing algorithms and protocols are intended to have. The routing protocols in logistics networks are designed to be dynamic, considering fluctuations in demand volume and selecting the most suitable transportation service available. They ensure that routing tables at each node are adjusted to accommodate service updates and incoming flows. The dynamic character of routing services has to be guaranteed by a sustainable and resilient digital infrastructure supporting real-time data exchange between pi-nodes/logistics service providers (dealing with routing services) and different pi-actors of the networks (pi-carriers, pi-shippers, other pi-nodes). For example, it is crucial that routing tables are updated according to network status (pi-means availability, flow level on specific routes, shipping requirements provided by clients, road congestion etc). Indeed, these protocols proposed by authors utilize a state-link routing approach, which requires additional storage but establishes a range of optimal paths with alternative options, offering flexibility in selection. They prioritize specific metrics aligned with logistics needs, such as cost, time, greenhouse gas emissions, while also considering means saturation. Moreover, in the event of container delays, these protocols have the capability to adapt by changing departure priorities or altering paths to maintain efficient operations.

Here, authors propose an algorithm running in a decentralized manner (algorithms that this thesis will not address) defining an interesting protocol. They imagine, first the LSP (logistic service provider) will run some protocols to get the resulting route, checking link-states and availability and defining a price. After the container departs from the initial node and reaches various intermediate nodes, each of these nodes, managed by a 3PL for instance, tries to dynamically exploit routing opportunities or avoid transport disturbances according to network real state. This process is made effective by the open monitoring property of PI and thus by exploiting upcoming flows of data (enabled by the digital capabilities of IoT).

Container consolidation on transportation means

The last research issue debated in this paper is the pi-container consolidation on transportation means. At every node within the Physical Internet (PI), pi-containers arrive asynchronously, accompanied by information regarding their next pi-link or intended/preferred destination. The protocol implemented at each node aims at optimizing the consolidation of containers based on their next destination and other factors (such as environmental requirements – cold chain for example, shipping service providers, shipper, consignee, time-related issues, future states). The objective is to efficiently group containers that share the same destination onto transportation means, such as trucks or trains, to enhance resource utilization and minimize overall transportation costs. In this optimization process, there is also a consideration for prioritizing urgent containers, ensuring they are shipped first to meet time-sensitive requirements. By consolidating containers based on their next destination and considering urgency, the protocol enables efficient and timely transportation within the PI network. This approach streamlines the movement of containers and contributes to the overall effectiveness and responsiveness of the logistics operations in the Physical Internet.

According to authors, the protocol optimizing the consolidation of pi-containers corresponds to the well-known bin-packing problem. In order to solve it, this paper prescribes the exploitation of heuristic approaches (best for large-scale problem) such as:

- First Fit (FF): Objects are loaded into bins based on their order of arrival. If there is not enough space in the first bin, the next bin is used without closing the first one. The process continues until all objects are accommodated.

- First Fit Decreasing (FFD): Objects are sorted in decreasing order of size and then loaded into the bins using the First Fit method. Sorting by size helps improve the quality of the solution.

- Best Fit (BF): Objects are sorted by arrival, and each object is attempted to be placed in the fullest open bin that can accommodate it. If no bin has sufficient space, the object is tried in the next fullest bin, and so on.

- Best Fit Decreasing (BFD): Similar to the Best Fit heuristic, but objects are first sorted in decreasing size order before being placed in bins.

If results of bin-packing problem are deemed unsatisfying, the algorithm is runned again up to the point when the departure is forced to not disregarding time-related shipping requirements. It is crucial to understand and highlight the dynamic interdependence between routing and consolidation protocol since the consolidation protocols has to take into account not only consolidation issues related to next hub/nodes to reach but to subsequent common destination whenever possible. This is made necessary in order to avoid as much as possible pi-container unloading, sorting, loading operations.

If the simulation model developed by the research, here analysed, was instrumental for authors to evaluate the impact of the interconnected PI networks, the same model is crucial for us to understand better the PI paradigm proposed and conceptualized by the same authors. Indeed, the multi-agent-based system described in this paper helps this thesis to understand the multi-perspective data exchange and protocols ruling Physical Internet. Specifically, they provide operating process and communications (during containerization, routing, and consolidation processes) between actors involved at the level of sourcing point (plant, warehouse, PI entry gateway) and of intermediate pi-hub.

In this scenario, each hub within the network has the ability to implement transportation protocols for every container, enabling them to assess the optimal match between the required service and the current state of both the hub and the container. By considering factors such as the hub's capabilities, available services, and the specific requirements of the container, the transportation protocols facilitate the decision-making process and ensure efficient routing and handling of containers throughout the network.

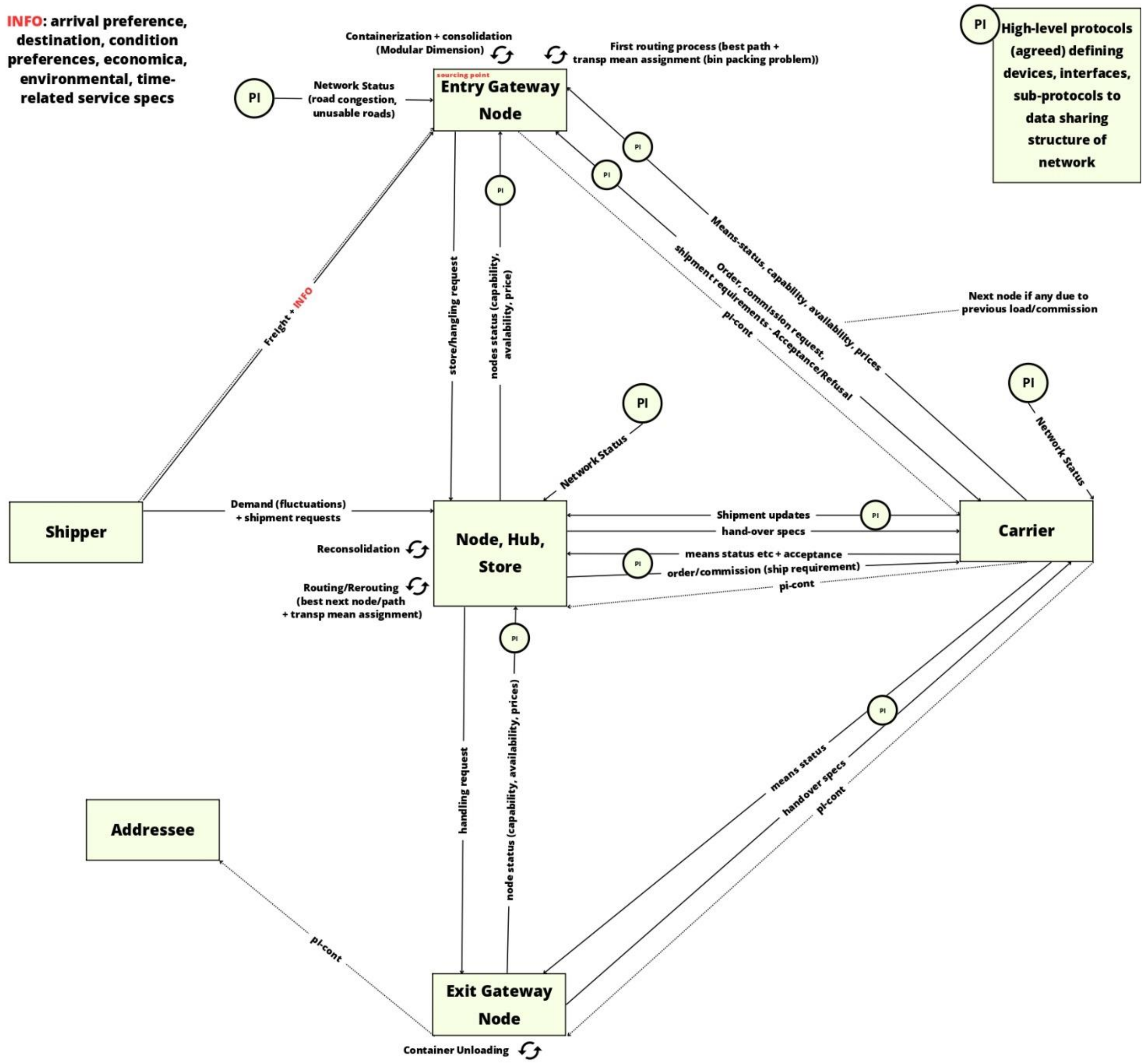

Figure 11 Protocols inferred from (Sarraj R. , Ballot, Pan, Hakimi, & Montreuil, 2014) – circles refer to an unspecified shared data structure

Routing Management in Physical Internet Crossdocking - Study of Grouping Strategies for Truck Loading – Pach, Sallez, Berger, Bonte, Trentesaux, Montreuil – 2014

The efficient management of crossdocking hubs is essential in the Physical Internet for facilitating swift and synchronized transfer of pi-containers between interconnected logistics networks. These new interconnected and modular-dimensioned pi-containers and their potential worldwide adoption would make organizations handle and store products from other companies and thus they can provide services and require services for pi-containers. In this context, this paper intends to define efficient grouping strategies for truck loading. These pre-loading grouping protocols are aimed at drastically reducing the overall "hub time" and specifically the overall loading time.

Hub Concept In Physical Internet (Focus On Road-Rail Pi-Hub)

According to literature and specifically to this paper, hubs in Physical Internet have many "breaking points" with respect to usual hubs in traditional logistics paradigm. A key innovation of the Physical Internet (PI) is the introduction of an open approach for suppliers and clients within the network. This means that the concept of pi-hubs, which serve as essential nodes within the PI network, is inherently designed to be accessible to any users who are certified within the PI system. These pi-hubs are capable of accommodating multiple sources and destinations, which are dynamically selected based on the specific requirements of the shipments.

Furthermore, if on one hand existing crossdocking hubs deals with all kinds of freight, on the other hand pi-hubs are designed to handle modular and standard pi-containers. This peculiar design provides many advantages in terms of connectivity and modularity, however it imposes substantial investments and mainly a well-structured process of encapsulation. The pi-containers encapsulation will be administrated by protocols matching best-fit pi-containers to products to encapsulate, given all the requirements provided by the shipper (size, weight, environmental requirements, service level etc). In addition to this, standardized modular pi-containers opens the way for high automation and reactiveness in routing, sorting, and moving pi-containers within the pi-hub. It would be made possible by flexible network of pi-conveyors in charge of decomposition, sorting and re-composition. This automated network would need to be strictly interconnected to other processes of pi-hub, such as routing service. In this regard, in order to efficiently manage crossdocking activities, this network needs to be fed in input by data like pi-means-container assignment, dock assigned to trucks loading, decomposition/composition orders etc. In this context, this paper highlights the importance of designing pi-containers with informational, communicational, and decisional abilities, capable to play an "active" and "reactive" role in the crossdocking processes we just wrote about (and not only).

This paper focuses its attention on the illustration of a road-rail pi-hub, necessary to carry out smooth interconnections between trains and trucks in shortest time. After wagons are unloaded from pi-containers, sorting and manoeuvring areas enables, through grids of pi-conveyors, addressing and routing pi-containers towards different gates (designated thanks to optimization algorithms). One of the requirements to ensure that the assignment of different trucks to the gates is scheduled efficiently is for the PI-hub to know the carriers' plans in advance. Very often, the PI-carriers plan their activities within a relatively short time frame, imposing the need for nodes to have a dynamic and flexible system that determines the sequence of inbound and outbound transporters at the gates. In addition to this, dynamic protocols are needed even for pi-containers allocation to transporters. These protocols have to define the most appropriate loading of trucks according to common destination, trucks' capacity, and pi-carrier availability to carry out the transfer at precise conditions provided by shipping requirements. Once the allocation is completed, pi-hubs have to be ready to route pi-containers across pi-hub to reach the right gate to be loaded on the right truck. This last operation, according to literature, has to be carried out exploiting interconnectivity and communication between pi-conveyors and "informed" pi-containers.

Of course, any type of external (changing incoming flows, pi-mean delayed etc) or internal perturbations (dysfunctions to conveyors) needs to be detected immediately in order to let management and protocols to dynamically react (maintenance orders, reschedule and reassignment of gates, conveyors etc). In the proposition of this protocol, authors consider pi-containers empowered with communicational and decisional capabilities going to play an active role in creating groups to consolidate.

Grouping Approach And Strategies

The most interesting insight that this paper contributes to literature is the conceptualization of grouping protocols (what literature calls pi-containers consolidation) and subsequent demonstration of their effectiveness. In fact, an interesting solution for optimizing the transfer of pi-containers is presented here: consolidating multiple small pi-containers in front of the truck before loading and treating them as a single composite pi-container during the loading process.

According to the proposed protocol, four activities characterize the process: proposal, answer, decision, choice diffusion.

(1) Proposal: The initial π-container, upon reaching the destination truck, sends a "grouping proposal" to identify potential π-containers that can be grouped and loaded together with it.

(2) Response: The relevant π-containers respond to the proposal by providing their respective arrival times, physical attributes (weight, volume, T° required etc), geo-characteristics of the orders (destination, next unloading node etc) and time-related constraints.

(3) Decision: The initiating container selects the π-containers based on different factors:

- The grouping size limit, determined by the chosen strategy, which sets the maximum number of π-containers in a group.
- The arrival times communicated by the other π-containers. The initiating container prioritizes those with the earliest arrival times to form the group until the size limit is reached.
- Future states (such as common hub destination where pi-containers are going to be unloaded)

(4) Choice dissemination: The initiating container communicates to the selected π-containers their specific positions within the group. Simultaneously, it notifies the unselected π-containers of their exclusion.

Using this approach, three strategies can be employed to determine the grouping size limit. Firstly, all containers destined for the same truck are grouped and loaded together without a limit (i.e., an infinite limit). Secondly, the number of containers in each group is statically limited to avoid disrupting the loading process of neighbouring trucks. Lastly, the number of containers in each group is dynamically limited by extending them if the adjacent gates remain unutilized (no truck assigned to the neighbouring gates). This last strategy imposes a communication protocol that informs about the adjacent gate's status.

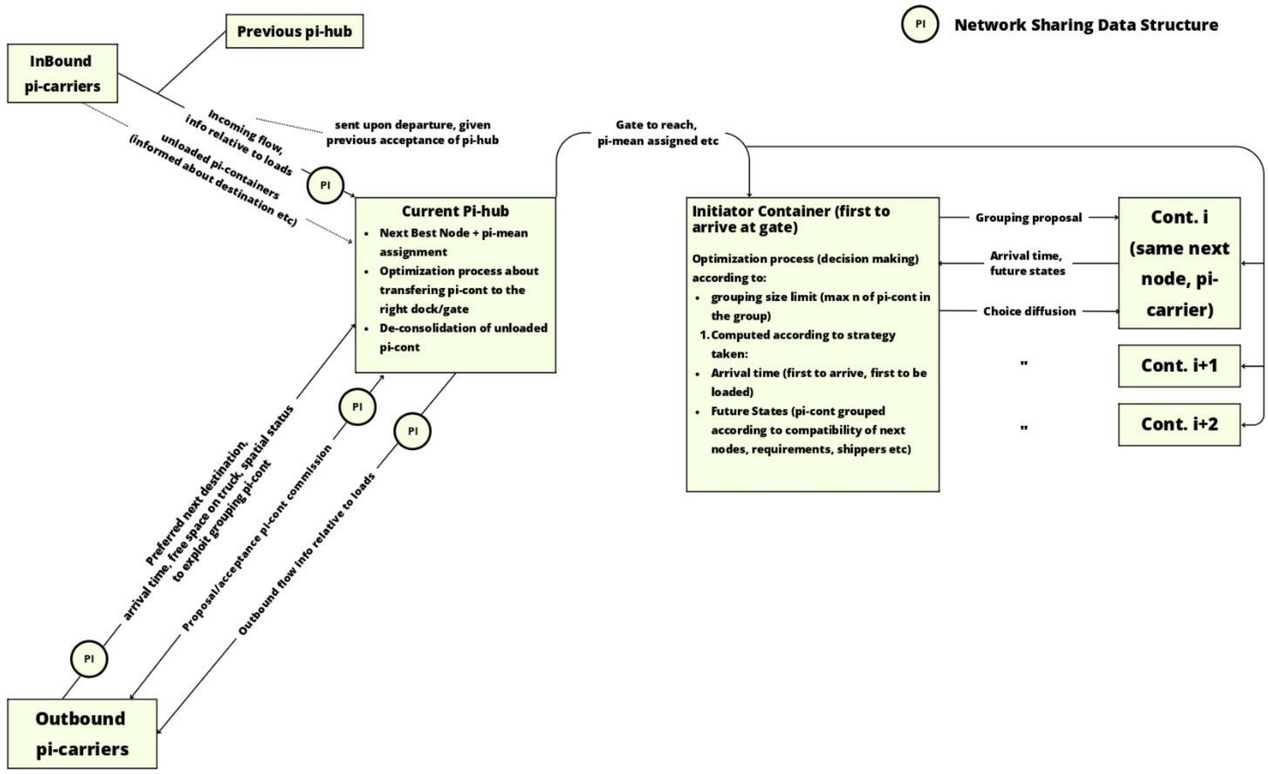

Figure 12 Protocols inferred from (Pach, et al., 2014) – circles refer to an unspecified shared data structure

A Proposal for an Open Logistics Interconnection Reference Model for a Physical Internet – Colin, Mathieu, Nakechbandi – 2016

This paper introduces the New Open Logistic Interconnection reference model (NOLI), designed for the Physical Internet, inspired by the OSI model for data networks. It compares the NOLI model with the OSI model, TCP/IP model, and the OLI model proposed specifically for the Physical Internet by Montreuil. The NOLI model stands out from the OLI model by incorporating physical object definitions across multiple layers, placing containerization and de-containerization operations in the topmost layer, and aligning closely with TCP/IP and OSI models. This contribution enhances the understanding and development of a reference model for the Physical Internet, facilitating efficient interconnection and logistics operations.

In the section below, the NOLI model is described in all the sevel layers that composed it.

Noli Model (New Open Logistics Interconnection) – Seven Layers – Protocols

The OLI model proposed by Montreuil deviates from the OSI model in several aspects, despite maintaining a similar seven-layer architecture. The NOLI model being presented in this paper also adheres to the seven-layer structure of the OSI model. Unlike how the authors presented the model within the paper under analysis, in the context of this thesis it was decided to report the description of the individual layers in descending order and thus from the top layer down to the lowest layer. This choice was taken in order to give a better understanding of the services provided by each layer, data exchange among layers and protocols in actions among adjacent layers and among same layers of different actors. The NOLI model reported is made of the following 7 layers (top-down): Product Layer, Container Layer, Order Layer, Transport Layer, Network Layer, Link Layer, Physical Handling Layer.

- *Product Layer*: The Product Layer serves conceptually as the Entry and Exit Gateway of Physical Internet. Indeed, this is where products and goods to ship are containerized and decontainerized in the most suitable pi-containers according to shipping requirements and contract established among parties (start nodes and shippers/clients). Therefore, the Product Layer makes it possible the establishment of any type of contracts between parties (production, supply, distribution, shipping contracts) and this implies a substantial data exchange between those parties. Specifically, the data exchange involves purchase orders, delivery instructions (sourcing location, destination, possible cold chain requirements, delivery time), INCOTERM specifications etc. Most of these data are delivered from clients/shippers to pi-nodes or anyone managing data enabling products to ship enter the Physical Internet networks (once encapsulated). Another crucial task of Product Layer is defining possible products or goods that can be encapsulated inside a pi-containers and be handled by PI logistics.
- *Container Layer*: The crucial role authors entrusted to Container Layer is to define physical characteristics of pi-containers allowed to flow and be part of PI network. Specifications such as modular sizes allowed, weight, materials, hardware and software to enable pi-containers to be interconnected and responsive are designed and managed by this layer. In the potential innovative path of Physical Internet and in turn of pi-containers we can think both to a "spontaneous" (bottom-up) or "induced" (top-down) emergence of a dominant design capable to satisfy most of the requirements coming from the logistics market. This reasoning keeps being valid also for pi-means, pi-nodes and all other pi-constituents requiring peculiar design to be part of PI.

  Furthermore, following the model proposed by this paper, once received pi-containers with all related information by the upper layer (contract info: weight, volume, required T°, destination, sourcing point, delivery time etc), Container Layer checks pi-containers' physical integrity and ,in case it is necessary, in specific specialized nodes it manages maintenance of pi-containers, retrieving of empty or lost pi-containers (signalled from the Order Layer) and R&D activities related to modular containers.

Finally, this layer combines the received pi-containers into "sets" according to their characteristics and forwards them to the lower layer, the Order Layer.

- *Order Layer*: The Order Layer receives sets of pi-containers from the Container Layer, with an initial starting and a final ending location for each set. Here, the dispatch note associated to each pi-container (for each set) is established and pi-containers assigned to orders. Indeed, the Order Layer divides or combines sets into "orders" according to multiple factors like deadlines, characteristics of pi-containers, client wishes such as sub-orders, starting and ending locations. Priorities and deadlines "flags" are attached to each new order entering the PI network. Besides this, the Order Layer monitors possible issues related to established contracts/submitted orders. For instance, it checks if the final ending location accepts dangerous materials or anyway if that node is coherent with shipping requirements of that order.

  Moreover, a crucial role the Order Layer plays is to manage transactions relative to orders. It sends payment requests, administrates fees for pi-hub, pi-carrier services. Finally, it signals damages/loss of pi-containers to the above Container Layer.
- *Transportation Layer*: Transport Layer receives orders made of pi-containers from Order Layer with relative initial starting and final ending locations and divides and combine them into "loads". Consequently, it oversees the entire trip of each load from its starting point to its destination. Indeed, here the shipping companies (not necessarily providing transportation services on their own) play a crucial role taking the commission directly from the client/shipper and overseeing the entire end-to-end trip. They check also if the final ending location is able to handle that load as far as its capacity and availability are concerned. In this context, initial departure, current location and final arrival of each pi-unit is communicated to the upper layer (Order Layer) ensuring that deadlines are respected. Managing the entire end-to-end trip requires an input of data even from lower layers. Indeed, the Transportation Layer is fed by Network Layer with network status (pi-means, pi-containers, pi-nodes) and routes defined in lower layer.
- *Network Layer*: Network Layer receives in input loads of pi-containers from the upper Transportation Layer with initial starting and final ending location. Then, it divides and/or recombines received loads into "blocks". The critical service provided by this layer is the computation and management of routing. Each block is routed from initial

starting location to final one through multiple intermediate pi-nodes. In order to carry out this task, this layer needs in input substantial data to process. Data demanded from Link Layer are link status, pi-containers-pi-means assignment, road congestion and traffic situations on network segments and potential receiving nodes status (in terms of capability, availability, congestion). Since the bulk of data to manage could be huge, this layer is in charge of managing and maintains data structure crucial to compute and updates best paths for the blocks. Data structure management can be thought about as decentralized (in different nodes/actors of the chains) or centralized (at least at network level).

- *Link Layer*: Link Layer takes care of individual steps (individual point-to-point movement – maybe between subsequent pi-nodes along singular pi-segments). Receiving blocks from Network Layer and routes attached to them, it divides and/or recombine them into "shipments" and allocates a pi-means to each shipment to handle it for one step, to carry out transfer along one pi-segment. Therefore, Link Layer manages the handover of a block from a company or operator to another. This layer recombines physical status forwarded by the Physical Handling Layer into their digital mirror and assures its consistency.
- *Physical Handling Layer*: According to this paper, Physical Handling Layer receives shipments of pi-containers and the identification of the pi-means allocated to each shipment from the Link Layer. Consequently, this layer manages the scheduling ot the pi-containers on those pi-means (along pi-links and within pi-nodes) or pi-movers (within pi-nodes) and the mapping of pi-containers (which one should be above on specific trailer etc.). This activity is enabled by another service provided by this layer, namely the management of states and locations of pi-means (availability, capability, predefined routes, constraints, trailers space availability etc.), pi-movers, pi-containers (waiting, carried, done etc.). Moreover, at this layer different actors give orders to pi-means/pi-movers and from pi-constituent receive problems alert signalled to the upper layer.

  Another crucial role of the Physical Handling Layer is the definition of the physical characteristics of the pi-constituents in charge of physically moving pi-containers (ships, trucks, cranes, belt conveyors) in order to design efficiently interfaces between them and in turn allowing easy unloading, loading, sorting processes.

First of all, it is important to provide clarification on the terminologies used in the paper but not extensively elaborated upon. These terms include set, order, load, block, and shipment.

Although this paper does not provide in-depth explanations of these terms and their practical significance within the context of the Physical Internet, we have considered them as essential "units" that are managed by different layers changing at each layer as per the their specific requirements. These units are always composed of pi-containers, which are the fundamental units in PI, but they are combined differently to facilitate efficient management across the different layers.

Another point to address is the punctual difference between the other models (OSI and OLI) and this NOLI model. The OLI model locates all definitions in the lower layer (Physical Layer), on the contrary this paper prescribes to establish definitions in distinct layers, when pi-constituents first appear. Indeed, in the NOLI is the Product Layer that defines usable cargoes and their specifications (exact identification of the type of cargo, its characteristics such as perishable/fragile etc). Then, Container Layer defines characteristics for pi-containers (size, cold chain enabled, hardware and software specs). Instead, pi-means are defined in the lowest layer (Physical Handling Layer) as in OSI they are defined electronic components.

Another crucial difference is for the containerization/de-containerization process. According to authors everything below the top layer must have to do with pi-containers and therefore the Product Layer is considered as the logical entry and exit gateway of the Physical Internet (layer where products enter PI network and are encapsulated to access lower layers).

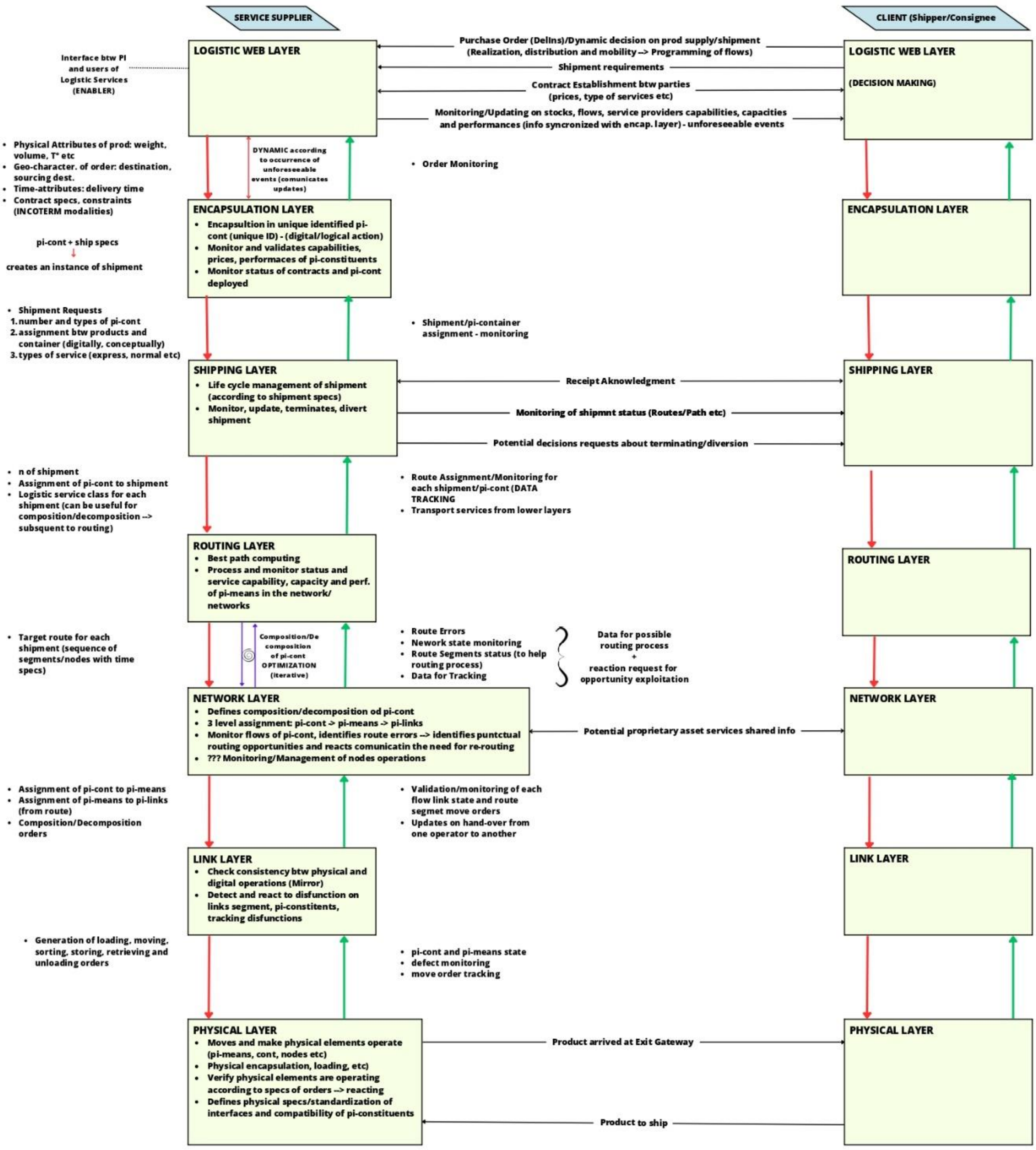

Figure 13 The seven layers of the OLI model as inferred from (Colin, Mathieu, & Nakechbandi, 2016)

Routing the PI-Containers in the Physical Internet using the PI-BGP Protocol – Gontara, Boufaied, Korbaa – 2018

The Internet has a scalable and adaptable routing system facilitated by Autonomous Systems (AS) peering with each other using the Border Gateway Protocol (BGP). On the contrary, authors affirm that trust between logistic service providers in the physical world is limited, hindering efficient routing. Nevertheless, Physical Internet, with its standardized PI-Containers and Internet-inspired protocols, has the potential to address this challenge.

Therefore, this study proposes a new routing approach called PI-BGP (Physical Internet-Border Gateway Protocol), equivalent to BGP on the Internet.

Reasoning On Routing Protocols

This paper explores the application of BGP-like protocols in routing PI-Containers within the Physical Internet. By treating logistic service providers (LSPs) as Physical Internet Autonomous Systems (PI-AS), each with their own routing protocols but adhering to common standards, interconnection, and cooperation among LSPs can be achieved. The existing literature utilizes the Vehicle Routing Problem (VRP) and shortest path algorithms to optimize the routing of vehicles. However, the paper proposes a shift in perspective, considering vehicles as links with different states rather than flows, and emphasizing the importance of PI-Containers as the primary focus for dynamic routing within the Physical Internet and as the sole flow of the Physical Internet.

The proposed routing protocol in the Physical Internet utilizes the Dijkstra algorithm to find the shortest path between nodes, considering factors such as lead time, logistics cost, and CO2 emissions. It addresses three main challenges: container filling, flow routing, and container grouping. Unlike previous routing methods that focused on one-way dispatching, this routing approach considers the movement between neighbouring PI-Hubs, aiming to maximize the flow of PI-Containers and minimize delivery times, similar to the improvements brought by the Border Gateway Protocol in the Internet.

Physical Internet - Border Gateway Protocol (PI-BGP)

It needs to be acknowledged how standards can be solutions for improving operational compatibility and coordination. Standards imply lock-in and at the same time adaptation and adaptability. For these reasons, it is crucial to ensure a sort of continuity between logistics and Physical Internet.

Between starting nodes and final destinations, the routing protocol proposed by authors is intended to find an agreement on the number of PI-Hubs stops, the time-related issues of transportation and wait and finally on costs from different sources. The PI-Hubs are considered as nodes of the Physical Internet and can be part of a same PI-AS or different ones if the routes are concatenated between them. This calls for protocols and standards in order to make different PI-AS communicate and let pi-containers cross smoothly PI-AS borders to reach final destination.

To this purpose, this paper prescribes what standards in the PI-BGP should take into considerations. First of all, PI-Containers dimensions should be standardized to allow smooth transition between two different pi-means, pi-nodes, PI-AS networks. Moreover, the switching from crossdocks to PI-Hubs is deemed fundamental to allow faster flow and quick unload activities. Pi-containers have to be sorted and transferred to the right dock to be loaded again onto the next pi-mean to head forward next node. Finally, communication between PI-BGP nodes has to be structured and standardized since data exchange is at basis of efficient coordination. According to authors, these communication standards prescribe the following data for different actors:

- Forwarding PI-AS: PI-Containers nature, dimensions, and weight
- Receiving PI-AS: availability for PI-containers, different costs for available positions, time estimate.
- Different roads and PI-Hubs conditions.

Finally, this paper proposes a case study on which it is performed a simulation. For our research purpose, we will report only the case study description giving insight on the dynamic attributes of the conceptualized routing protocol able to resist to perturbances (in this case road congestion). This case study, following the setting of the entire paper, presumes that between two adjacent PI-Hubs, several trucks are traveling sticking to the pre-established and optimized routes, set by their own LSPs.

According to the case study, a PI-Container initially departs from starting location S to neighbouring PI-Hub A on the shortest path. However, congestion occurs between PI-Hub A and B. The delay is communicated, and a new route is established to PI-Hub A1 with lower re-routing times. The PI-Container quickly unloads, sorts, and loads at PI-Hub A, then departs to PI-Hub A1 on a different truck. From there, it continues to PI-Hub B on a decongested route, avoiding delays and maintaining flow.

The main advantage of the PI-BGP is its ability to dynamically change the next PI-Hub in the event of delays, unavailability of routes or trucks. This enables re-routing to neighbouring PI-Hubs, preventing delays and congestion at the PI-Hubs, and ensuring that PI-Containers do not have to wait for their predetermined routes to become available again. The effectiveness of the PI-BGP depends on the exchange of information between PI-AS to determine the optimal path, which may not always be the shortest. Efficient information exchange is crucial for this process, and a centralized system that receives and manages this information can greatly enhance its speed and effectiveness. There has been a proposal for an autonomous distributed information system for logistics control to manage the flow of items efficiently and dynamically (Ikkai, Oka, Komoda, & Itsuki, 2003). However, for achieving seamless interoperability between Logistics Service Providers (LSPs) acting as PI-AS in the Physical Internet, this proposed system needs to be implemented as a centralized solution.

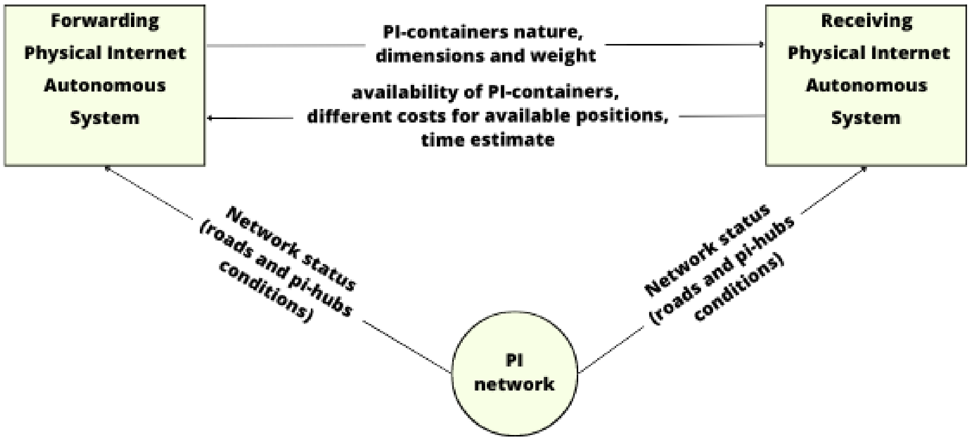

Figure 14 Protocol inferred from (Gontara, Boufaied, & Korbaa, 2018) – circles refer to an unspecified shared data structure

Multi-Objective Sustainable Truck Scheduling in a Rail-Road Physical Internet Cross-Docking Hub Considering Energy Consumption - Chargui Bekrar – 2019

The concept of Physical Internet (PI) has been introduced as an innovative approach to establish a sustainable global logistics system within the supply chain. A key element of the PI paradigm is the use of modular and standardized PI-containers, which enable the movement of products through PI-nodes, including PI-hubs, using collaborative routing protocols. This study specifically aims to optimize operations in a Rail-Road PI-Hub cross-docking terminal, focusing on improving efficiency and effectiveness in handling and transferring goods.

This study focuses on scheduling outbound trucks and routing PI-containers in a Rail-Road PI-Hub cross-docking terminal. The goal is to minimize energy consumption and cost. A Multi-Objective Mixed-Integer Programming model is used, along with two meta-heuristics, to find optimal or near-optimal solutions. The approaches offer computational efficiency and contribute to optimizing operations in Rail-Road PI-Hubs.

The analysis of the paper will first present a brief description of the literature review provided by the authors. Then, it will show the problem description, working assumptions specifically focusing on data input/output of the Multi-Objective Mixed-Integer Programming (MO-MIP) model proposed by authors in this paper.

The Physical Internet (PI) relies on PI Cross-Docking Hubs as essential components of its network. Various functional designs have been proposed for these hubs, including Road-based transit centers and Road-Rail PI-hubs, with a focus on key performance indicators from the customer's and operator's perspectives (Meller R. , Montreuil, Thivierge, & Montreuil, 2012) (Ballot, Montreuil, & Thivierge, 2012). Research has been conducted to address control and optimization problems related to Road-Rail PI-hubs, particularly in the context of PI-sorters, which play a crucial role in routing PI-containers. Intelligent reactive approaches, such as multi-agent systems, have been explored to optimize the routing and grouping of PI-containers in Rail-Road cross-docking PI-hubs, considering factors like evacuation time and tardiness of trucks.

Standardized autonomous modular PI-containers are fundamental to the Physical Internet paradigm, enabling efficient routing within PI-hubs and across the transportation network (Sallez, Pan, Montreuil, Berger, & Ballot, 2016). The concept of active PI-containers, capable of making decisions and optimizing handling and movement operations, has been introduced. Hybrid control architectures have also been examined, evaluating performance under internal and external disruptions. Optimized and Reactive hybrid Control Architectures (ORCA) have been proposed to study PI-container routing strategies in perturbed environments using predictive and reactive techniques (Vo, Berger, Bonte, & Sallez, 2018).

Problem Description And Working Assumptions

In this section, the Rail-Road PI-hub cross-docking process is described, outlining its various functionalities and layout. The Rail-Road PI-hub serves as a PI-node designed to transfer PI-containers from trains to outbound trucks. It primarily consists of a PI-sorter and two manoeuvring areas located in front of the train and loading docks. The cross-docking process begins by unloading PI-containers from the wagons. Subsequently, the PI-containers are routed to the outbound docks, grouped based on their destination, and then loaded onto the respective outgoing trucks.

The literature lacks focus on sustainability objectives and constraints in cross-docking scheduling. Prior studies have primarily examined energy consumption in traditional terminals, neglecting sustainability considerations. This research addresses this gap by minimizing energy consumption and outbound truck costs in Rail-Road PI-hub cross-dock truck scheduling. These objectives conflict as reducing energy consumption may increase truck usage and costs. To overcome this, multi-objective approaches are proposed, including a mathematical model (MO-MIP) and two meta-heuristics (MO-VNSSA and MO-VNSTS). The study adopts a specific order for minimizing the two objectives as determined by decision-makers. Furthermore, it accounts for varying lengths and destinations of PI-containers, ensuring trucks only load containers with the same destination.

Authors formulating the problem as Multi-Objective Mixed-Integer Programming (MO-MIP) model aim at finding the grouping of the PI-containers and the assignment and scheduling of the trucks at the docks. This optimization problem has to be designed while minimizing two conflicting objectives: the energy cost for using PI-conveyors to handle the PI-containers and, at the same time, the cost of using the outgoing trucks. This paper provides a clear definition of input parameters/data that this model needs, and that Cross-Docking Hubs have to gather in order to achieve necessary output variables (herein defined too).

The main input Data are: pi-containers lengths, position of pi-containers in train, pi-containers destinations, energy consumption cost for one pi-conveyor unit, outbound truck cost for each destination, dock positions, truck capacity. On the other hand, resulting output variables are: pi-containers assignment and grouping in the trucks, trucks' assignment and sequence at the docks, start/end time of loading trucks, energy consumption for routing the pi-containers within the pi-hub facility, total cost of outbound trucks, trucks' destination.

The model was then solved by authors and the obtained results showed that the two meta-heuristics were able to generate near optimal and optimal solutions within short computational times. This result led to the validation of this model opening it to further research considering perturbations occurring in the PI-hub facility such as trucks delays, customers changing orders at the last minute, etc.

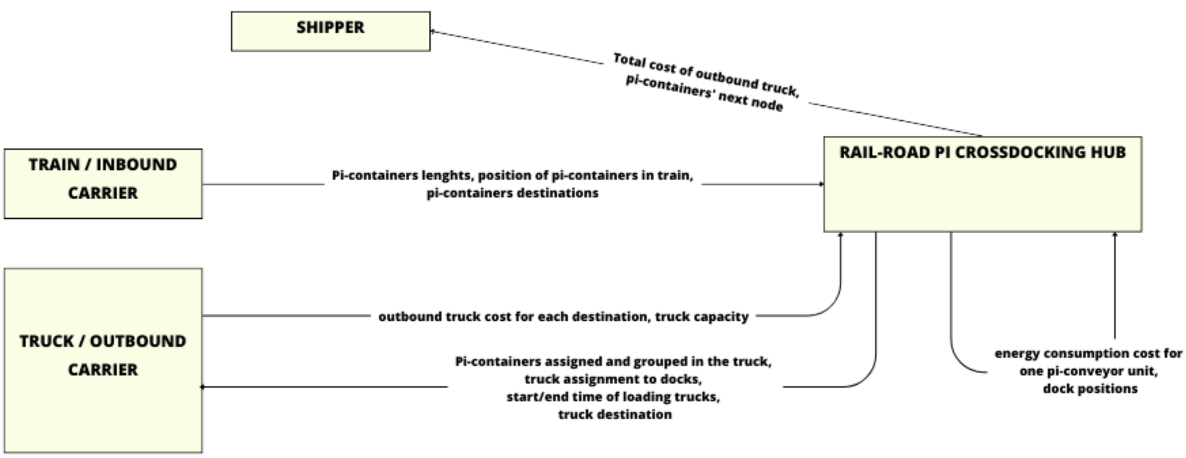

Figure 15 Protocols inferred from (Chargui, Bekrar, Reghioui, & Trentesaux, 2019)

Rule-based incentive mechanism design for a decentralized collaborative transport network – Lafkihi, Shenle Pan, Eric Ballot – 2019

Starting from the Physical Internet as a reference example, this paper discusses a combination of an incentive mechanism along with a set of collaborative rules within a decentralized collaborative transport network (CTN). This research effort aims to significantly increase the sustainability, efficiency, and effectiveness of the logistics network without compromising the individual profits of independent carriers.

In this regard, authors make three fundamental contributions to the literature. First of all, they present clear and useful insights about how to detect and design a set of protocols going to regulate and mediate interactions between actors in the PI-like network. Those protocols aim at sustaining high levels of effectiveness, efficiency and sustainability of the network and are based on freight transport KPIs. Secondly, this paper provides an incentive mechanism equipped with an auction-based optimization model alongside the rules for collaborative transport request assignment. Lastly, a multi-agent simulation model is proposed to evaluate the performance of the protocols mentioned before.

Methodology

With the purpose of optimal resource allocation in a decentralized collaborative transport network (CTN), authors try to frame the mechanism design problem proposing a three-step methodology. This approach aims to design an efficient and effective mechanism for resource allocation in the CTN, promoting collaboration among carriers while ensuring optimal individual outcomes. First, they model the bidding price strategies of carriers. Second, they extend the traditional auction mechanism by incorporating collaborative rules. Lastly, they develop a simulation model to assess the performance of the protocols implemented.

This paper studies seven KPIs corresponding to three main objectives effectiveness, efficiency and sustainability. Specifically the KPIs are:

- Total transport cost (€)
- Total carrier profit (€)
- Loading factor (%)
- Total transport (tonnes.km)
- Total number of delays
- Number of unallocated requests
- Vehicle-kilometres

Collaborative Mechanism And Protocols

The actors involved in the protocols proposed by this paper are three: shippers (service buyers), carriers (service sellers), auctioneer (here interpreted as pi-nodes taking care of the auction process and facilitating interaction between carriers and shippers). In this paradigm, it is considered a decentralized network of collaborating freight carrier companies in which carriers receive new transport requests either from shippers for contracting or from other carriers for subcontracting. Carriers plan their operations and routes on this basis. To determine prices of requests, carriers rely on transport costs.

Collaborative rules

This paper defines a set of collaborative rules and consequently assess their impact on each of the KPIs presented before. The rules defined are:

Rule 1: en-route reallocation. At some hubs in the network, shipments must be reallocated to other carriers proposing a lower price. This rule enables the co-delivery of requests and therefore it motivates a carrier to sell any unused capacity to a carrier who can use it to transfer their own cargo. Reallocation in a decentralized collaborative transport network optimizes vehicle usage by reducing empty runs and maximizing capacity. Carriers can exchange capacity, subcontracting shipments to others for cost savings. This process generates additional profits for carriers, enhancing overall efficiency and revenue generation in the transport network.

Rule 2: lowest price and best reputation win. If there is competition, shipments must be allocated/reallocated to the carrier proposing the lowest price. If two carriers are tied for the lowest price, then the carrier with the best reputation will win the shipment auction.

Rule 3: no price increase. Once a price is promised to the shipper, it cannot be increased when transferring the request from one carrier to another in the event of reallocation. This rule is in line with the objective of the carrier to increase its profit while guaranteeing shipper satisfaction.

Rule 4: individual responsibility. Each carrier is responsible for any delays they cause and pay the associated penalty. Being responsible for their delays, carriers are more incline to manage carefully lead times and route choices.

Rule 5: no halfway drop-out. If there is no possibility of reallocation, the carrier in charge must transport the request acquired from the origin to the destination. The aim is to guarantee the quality of service in the network. To do this, a bidder (carrier) must submit a price (for allocation or reallocation) that covers the entire route from the origin to the final destination.

Combinatorial auction mechanism

In the model here presented, it is utilized the First Price Sealed Combinatorial Auction as auction mechanism. In this auction, all carriers simultaneously submit their sealed bids to preserve the privacy of carrier information (Kleijnen & Van Schaik, 2011). In the multi-agent approach, used here to model the auction, the requests can be bundled for cost reduction, thanks to economies of scale (Gansterer, Hartl, & Vetschera, 2018). It follows the protocol proposed:

Step1: shippers submit the new delivery request information (destination, time-related info, freight requirements, price-related info) to the auctioneer (pi-node in this thesis' perspective). Then also the carrier interacts with the auctioning agent submitting the in-transit request information (which orders to sub-contract to other carriers).

Step2: after gathering all the necessary information, the auctioneer consolidates the delivery requests in bundles and shares the relevant details, such as volume and route, with the carriers. The carriers, in turn, must carefully assess the available requests from the pool to determine which delivery request bundles align best with their capabilities. The factors (no related to price of course) regulating this process of decision making can be route compatibility, carrier capacity. After this choice, carriers have to finalize their optimal bidding strategy coupling the chosen request bundles to bid for and the price to submit to maximise their profits.

Step3: after all, interested carriers submit their bids, the auctioneer undertakes the winner decision process (WDP). The auctioneer then disseminates the results to the losing carriers while providing detailed information to the winning carrier and the shipper involved, including payment details. The winning carrier confirms the auction outcome and makes the required payments to subcontracted carriers. Meanwhile, the shipper pays transport service fees to carriers and auction fees to the auctioneer.

Figure 1 presents the cross-functional flowchart of the three actors involved in the auction process.

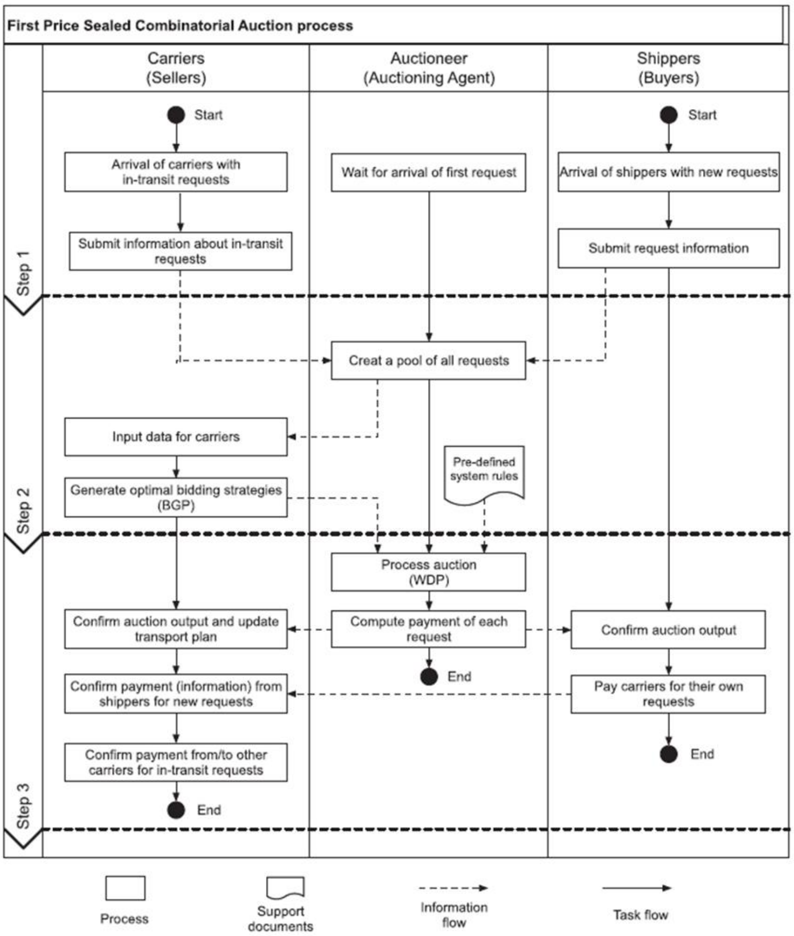

Figure 16 Cross-functional flowchart of the auction process in a period by (Lafkihi, Pan, & Ballot, 2019)

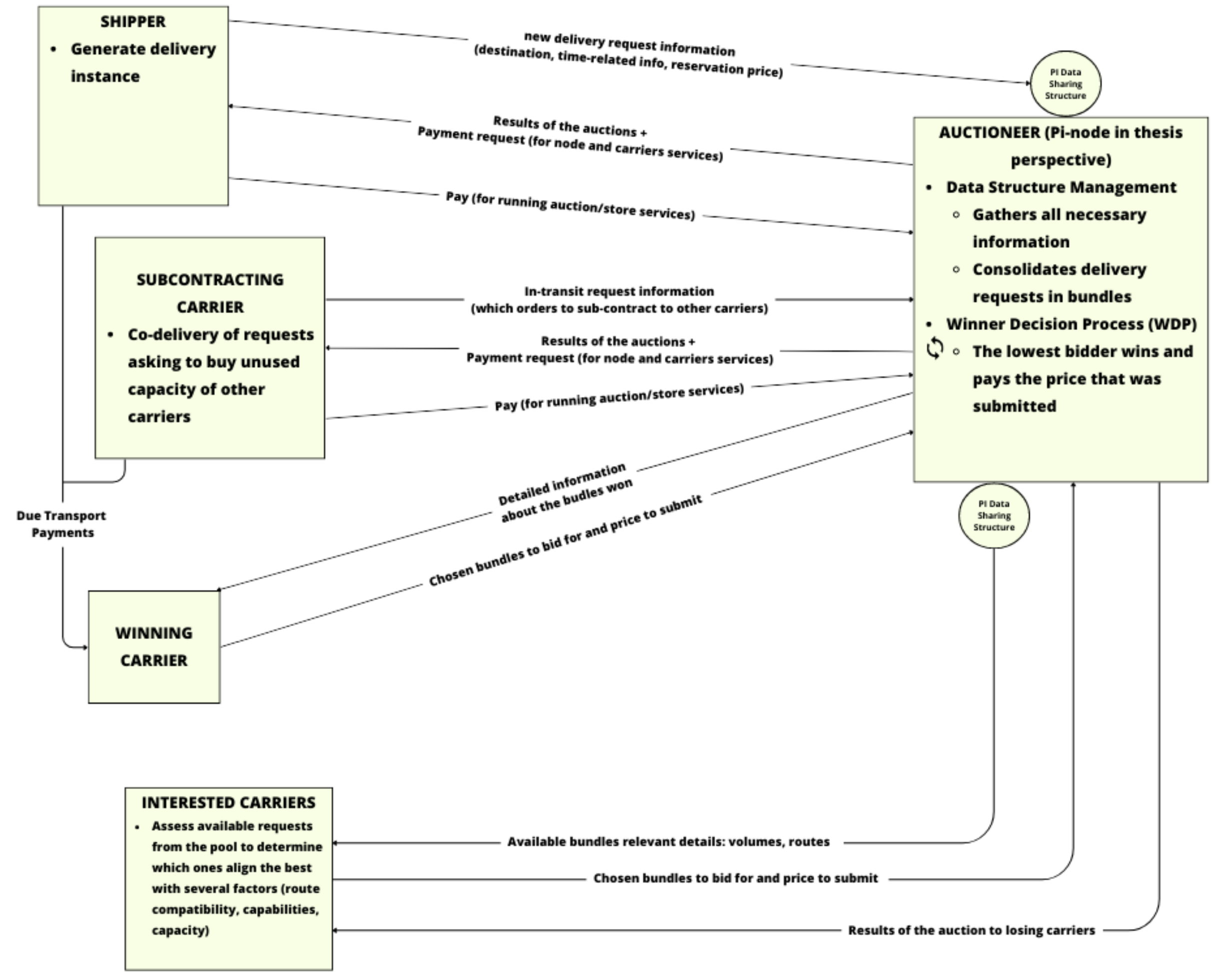

Figure 17 Protocols inferred from (Lafkihi, Pan, & Ballot, 2019) – circles refer to an unspecified shared data structure

Toward the Internet of Things for Physical Internet Perspectives and Challenges - Tran-Dang, Krommenacker - 2019

The Physical Internet (PI) is a global logistics system designed to move, handle, store, and transport goods sustainably and efficiently. It relies on high-level interconnectivity in physical, informational, and operational aspects, facilitated by intermodal hubs, collaborative protocols, and standardized, smart containers. PI leverages the Internet of Things (IoT) to enable end-to-end visibility and traceability through ubiquitous information exchange. By integrating technologies like RFID, WSN, GPS, and embedded modules, logistics systems become smarter, allowing for real-time tracking, transparency, and optimized decision-making. IoT adoption ensures shipment integrity, adherence to contractual agreements, and real-time monitoring of environmental conditions. The potential benefits of IoT in logistics include improved efficiency, reduced processing time, and enhanced product safety.

This article investigates the potential of IoT technology in the Physical Internet (PI) vision, proposing a π-IoT ecosystem that integrates IoT technologies, building blocks, and a service-oriented architecture (SoA) to support PI implementation. The main contributions include a comprehensive review of PI components and IoT applications in logistics, the proposal of an IoT ecosystem with essential technologies for PI, and the identification of barriers hindering IoT implementation in PI, suggesting avenues for future research and development.

Key Components Of Pi

- **Π-Containers**.To address the diversity of boxes and containers in logistics, the Physical Internet (PI) introduces three categories of π-containers: transport, handling, and packaging containers (T/H/P-containers). These containers have specific functions and dimensions. P-containers, the smallest in size, are used for directly packing physical goods. H-containers, of medium size, facilitate handling operations by temporarily storing a set of P-containers. T-containers, the largest, are used for transporting large volumes of H-containers and/or P-containers across different regions (Montreuil 2017). It is important for the dimensions of π-containers to adhere to international standardization guidelines. According to (Montreuil B. , 2011) (Ballot, Montreuil, & Meller, 2014), authors highlight which key information a pi-container needs to have:
  - Unique Identifiers: with the purpose of securing an adequate tracking, tracing and handling activities by different actors in the global PI network, it is deemed crucial to associate a unique identifiers to each pi-container. As a consequence, any customer or stakeholder can access real-time information (position, status of ordered shipment) thanks to applications enabled by IoT. On top of this, decision-making in logistics can be optimized thanks to advanced data processing (Big Data analytics, machine learning, artificial intelligence) leveraging on historical data associated to pi-containers activities.
  - Specification Information: this type of information deals with detailed description of pi-containers, both from the dimensional perspective (size, weight, etc.) and from the functional one (transport, handling, packaging such as cold chain requirements).
  - Monitored Conditions: another crucial information gathering in the context of pi-containers encompasses data monitored from the ambient environment (temperature, humidity, etc). This monitoring activity is aimed at guarantee required conditions for the content (comparing its state with predefined threshold) and, in case of imbalances detection, the pi-container has to be capable of communicating or reacting properly.

Moreover, pi-containers are responsible for ensuring the integrity of content detecting unexpected openings.

- **Π-Movers**. With the integration of ICT, the π-movers are transformed into active agents within the PI system. They can interact with π-containers and a PI management system (PIMS) to exchange important information, including identifiers, dimensions, and final destination. This information is utilized by the π-movers to make appropriate decisions.
- **Π-Nodes**. Effective management of the diverse types of π-nodes is crucial in the Physical Internet (PI) to efficiently process inputs and meet output requirements. These nodes facilitate complex logistics operations and can house a combination of π-movers and/or other embedded π-nodes to handle materials. Scheduling approaches, particularly for π-mover usage, significantly impact the utilization and efficiency of π-nodes. Optimization methods, such as heuristic, meta-heuristic, and multi-agent-based approaches, aim to minimize travel distances for π-containers to docks and optimize the number of π-trucks needed for transportation in road-rail π-hubs. Additionally, optimizing the operational schedule of π-trucks to minimize energy consumption enhances efficiency and sustainability in π-hubs. Efficient management and scheduling of π-nodes play a vital role in achieving desired performance within the PI network.

The availability of real-time information is essential for modelling and formulating optimization problems in the context of the Physical Internet (PI). In order to make informed decisions and improve operational efficiency, it is necessary to have up-to-date data on the state of π-nodes, π-movers, and π-containers. Information management systems that utilize emerging technologies, particularly Internet of Things (IoT), are well-suited for addressing this challenge. IoT technology enables the collection, transmission, and analysis of data from various interconnected devices and sensors. By integrating IoT devices within the PI network, information management systems can provide end-to-end visibility of logistics assets, including π-nodes (Qiu & Huang, 2013) (Qiu, Luo, Xu, Zhong, & Huang, 2015). This allows for a comprehensive understanding of the current state and location of containers, movers, and nodes within the network.

The real-time visibility provided by IoT-based information management systems has several benefits. IoT technology in logistics provides real-time asset monitoring and tracking, improving coordination and resource allocation. It enables accurate forecasting and optimization of routing and scheduling decisions, adapting to network changes. Integration with AI and data analytics enhances insights and optimizes operations by identifying patterns, trends, and inefficiencies. This leads to improved decision-making and overall performance enhancement in logistics.

- **Π-Protocols**. The Physical Internet requires standardized rules and agreements for efficient and sustainable movement, handling, storage, and transportation of π-containers, known as pi-Protocols. Inspired by Montreuil's literature, the authors introduce the OLI model, a seven-layered reference model comprising the physical, link, network, routing, shipping, encapsulation, and logistics layers. Each layer offers specific services to support logistics activities such as procurement, handling, production, storage, and transportation. Layering the services optimizes logistics management and enhances the efficiency of logistics activities.

Key Technologies For Π-IoT Realization

The enabling technology for π-IoT proposed by this paper can be grouped into four functional blocks: data-acquisition technology, connectivity technology, data processing, and middleware.

Data-Acquisition Technology: these technologies divide in three classifications crucial to the data acquisition and access: identification, sensing, tracking technologies. Authors refer to identification technologies talking about RFID, NFC, barcode, or QR code systems that could play a pivotal role in logistics-related applications. Indeed, identification systems in the PI context would consist of a set of smart tags and a set of readers, located on pi-constituents (pi, movers, pi-containers, pi-entry/exit gateways etc), capable of scan and read data stored in the tags. In this way the real-time tracking can be enabled in an efficient and open way. Moreover, sensing modules embedded in PI smart object are intended to detect status of objects and state of surrounding environment conditions in order to provide useful information to react or act accordingly. These systems can both activate protocols making smart objects react autonomously or share data with other systems in order to react to unexpected events detected or to carry out monitoring, controlling, prediction activities. Finally, tracking technology are at basis of logistics operation to provide tracking and tracing services to pi-nodes, pi-shippers (clients) and other pi-actors.

Connectivity Technology: This aspect deals with transmitting IoT data to devices and the cloud. Connectivity in the π-IoT ecosystem is challenging due to the presence of heterogeneous networks operating under different protocols. IoT gateways are used to enable data communication across various networks.

Data Processing: Daily logistics activities generate a significant volume of data that needs to be processed to gain insights for decision-making. Cloud-based services, such as PaaS, SaaS, and IaaS, are utilized to handle the data processing requirements. IoT data is transmitted to central cloud databases for processing, and the outcomes are delivered to subscribed applications. In this way, pi-nodes are enabled to compute reliable and optimal routes for pi-containers within the pi-nodes and across pi-nodes and networks.

Middleware: IoT middleware plays a crucial role in coordinating and distributing resources between IoT components. In the context of π-IoT, middleware developed based on the Service-Oriented Architecture (SOA) approach is effective. SOA allows subsystems to interoperate efficiently and is suitable for managing the complexity of logistics systems with numerous physical facilities. It integrates logistics processes and information, facilitating data exchange, collaboration, and visibility across the logistics chain in real-time (Bandyopadhyay & Sen, 2011) (Hammergren, 2009).

Building-Blocks Of Π-IoT

π-IoT can be built on three key building blocks, including smart objects, smart networks, and smart PIMS.

Smart Objects

Smart objects in the context of the Physical Internet (PI) refer to physical equipment and logistics assets, such as π-containers and π-movers, that are transformed into objects capable of perceiving and interacting with their environment. Smart objects consist of four main modules: data acquisition, connectivity, power, and processing. The data acquisition module collects relevant data through technologies like RFID, sensors, and tracking. The processing module performs tasks to enable smart functionality. The connectivity module facilitates communication and data exchange. The power module provides energy for all operational modules. These modules work together to create intelligent and interactive objects in the π-IoT ecosystem (Meyer, Främling, & Holmström, 2009) (Tran-Dang, Krommenacker, & Charpentier, 2017). For example, in the context of the Physical Internet (PI), π-vehicles, such as π-trucks, play a dual role. They provide real-time movement information through GPS systems to fleet management centers and also gather and transmit sensed status data, like engine speed and temperature, for early warning and potential maintenance activities. Furthermore, π-trucks act as fog nodes, allowing them to perform computation and communication tasks even while in motion.

In IoT systems, smart objects can store and exchange valuable data to enhance decision-making. For example, π-containers' embedded sensors can store two types of information: proprioceptive (related to the container's specifications) and exteroceptive (obtained through interaction with the environment) (Sallez, Pan, Montreuil, Berger, & Ballot, 2016). According to authors, in the IoT-enabled Physical Internet, common categories of exchanged information include metadata, state data, telemetry data, and commands.

• **Metadata**: Immutable specifications of smart objects, such as ID and manufacturing date, are read using identification systems like RFID and barcodes.

• **State Information**: Current object status, like CPU temperature and battery state, is periodically updated and transmitted to the central management system for real-time control.

• **Telemetry:** Information collected through sensing the environment and exchanging data with other objects or systems ensures identification, integrity, routing, conditioning, monitoring, traceability, and security. For efficient handling, storage, and automation, routing information is added to sensors' memory. To enable efficient routing, the routing information (previous/next/final destination address) of π-containers is stored in the sensor's memory, along with other data (Montreuil, Meller, & Ballot, 2010).

• **Commands**: Smart objects perform actions based on collected information. For example, a π-container may send an alarm command to a nearby management system upon detecting a potential risk.

Within the PI network, stakeholders access necessary data by interacting with agents, ensuring restricted access for security and privacy. The MODULUSHCA common data model comprises business data, shipment data, network data, and public data, facilitating information exchange among PI partners (Tretola, Biggi, & Verdino, 2015). Sophisticated data processing strategies, like big data analytics, are applied to derive insights from the vast amount of transmitted data.

Smart PIMS

A PIMS (Physical Internet Management System) is a network of computer-based systems [e.g., WMSs, transportation management system (TMS), and enterprise resource planning (ERP)], including specialized software and databases, that efficiently manages and controls logistics processes using data from the underlying IoT infrastructure. With a large number of π-containers and logistics assets, the smart PIMS should be distributed intelligently across multiple resources for effective management. For example, at the receiving site, inbound π-movers and π-containers are registered, verified, and scanned. The PIMS uses active subsystems to perform specific functions and allocate resources accordingly. π-containers are directed to appropriate locations using conveyors or carriers, considering their next destination and processes, while avoiding collisions and balancing loads.

Smart Network

Smart networks leverage computing technologies to process data efficiently. Edge computing and fog computing enable data processing and analysis at or near the network edge, reducing data transmission to central servers or clouds (Cha, Yang, & Song, 2018) (Sahni, Cao, Zhang, & Yang, 2017). This improves scalability, response time, and supports mobility. Combined with big data analytics (BDA), smart networks offer predictive analysis and reporting functions, enhancing data-driven decision making. A converged network is crucial for ensuring interoperability and supporting IoT applications and services, providing benefits like cost savings, simplified operations, and consistent policy enforcement through unified management.

Service-Oriented Architecture For Π-Iot

The paper presents an architecture for a π-IoT ecosystem that integrates logistics processes and information. The architecture enables real-time data exchange, responsiveness, collaboration, synchronization, and visibility across the logistics chain (Atzori, Iera, & Morabito, 2010) (Miorandi, Sicari, Pellegrini, & Chlamtac, 2012) (Xu, 2011). It consists of four layers: the physical layer, network layer, service layer, and interface layer for π-IoT in the context of the Physical Internet (PI).

- The **physical layer** focuses on acquiring IoT data from smart objects and networks using technologies like RFID, NFC, barcodes, and WSN. The collected data is preprocessed, categorized, and standardized to reduce the traffic load. For example, the information used to realize the four classes of the π-container (described for smart objects) can be classified into four corresponding levels.

    1) Passive Information: π-container specification and location for providing the tracking and traceability functions.

    2) Triggering Information: perceived from sensing and detecting by adequate sensors. Therefore, detected problems are sent to the PIMS as an alert message. Such information provides the monitoring function.

    3) Decision Process Information: obtained through the interaction and communication among proximity π-containers. The management of

incompatibility between π-containers is an example of services served by such information.

4) Self-Organized Information: π-containers are self-sufficient and are able to provide services based on the information obtained from the π-infrastructure in the previous class.

- The **network layer** is responsible for connecting heterogeneous pi-constituents and transporting aggregated information from the physical layer. It ensures the discovery and delivery of services as requested by users and applications, considering design concerns to meet the requirements of π-IoT.
- The **service layer** relies on middleware and advanced data processing technologies to integrate heterogeneous information and create valuable services. These services can include on-demand applications, traceability and tracking functions, monitoring, scheduling, routing, and notification services. The service layer also determines the locations to access the services, with smart objects acting as service providers.
- The **interface layer** addresses the challenge of accessing services due to the heterogeneity of smart objects. It enables universal access to services through devices like PDAs, handheld devices, smartphones, and computers. While universal plug and play (UPnP) is desirable, an interface profile is designed to accommodate the compatibility of standards and interfacing methods in the π-IoT system.

Framework artifact for the road-based physical internet based on internet protocols - Kaup, Steffen, Ludwig, André – 2021

According to the authors, in the context of road-based transportation, the Road-Based Physical Internet (RBPI) holds significant potential for reducing empty runs and underutilized trips. According to authors, implementing RBPI requires analysing deeply DI protocols and adapting them to the world of PI. To address this challenge, this paper proposes a new conceptual five layers model working on the Open Logistics Interconnection conceptualized in Montreuil et. Al (2012) (layered structured model proposed for Physical Internet) and the Open System Interconnection at basis of Digital Internet.

Road-Based Physical Internet Model

Aiming at transfer operating principles of the DI to the context of road-based freight transport, authors make use of design principles for reference modelling. Specifically, they use five distinct principles: analogy, specialization, aggregation, instantiation, and configuration. Each principle denotes a unique approach for re-utilizing methods or content from the original model to construct a target model. Following it is reported the 5-layered structure of the model resulting from the analysis activities of authors:

- *Layer 5: Aggregated Application Layer*. This layer stems from the aggregation of three layers of OLI model (Logistic Web, Encapsulation and Shipping Layers). In this layer information and goods are prepared for transmission/transport to their destination. Therefore, it is here that goods are encapsulated in the right pi-container addressing all requirements for product transportation (according to Info/Data accompanying freight). Information contains sender and destination addresses, treatment requirements, latest delivery date and the cost budget that firstly are sent by the shipper/customer and made them available to the network (searching for service providers willing to address the shipping request). On this layer according to authors thesis, protocols such as RIP (Routing Information Protocol), OSPF (Open Shortest Path Information First) and BGP (Border Gateway Protocol) implement different routing strategies creating and updating dynamically routing tables, so called in Digital Internet context. Indeed, routing tables computed at starting nodes (PI entry gateways) are dynamically adjourned according to pi-network, pi-means, pi-nodes status available to pi-actors dealing with routing tables.
- *Layer 4: From Transport Layer to Routing Layer*. From the upper layer, the Transportation Layer receives delivery order (data, contracts/service specifications, containerization details), routing tables (continuously updated) and from the lower layers the data delivered are about current network status. Then shipments are broken up into sizes that are transportable by standard sized containers or network defined standard transport mechanisms (Liesa, 2020). If freight is decomposed into sub-components, these sub-components and their order must be provided with instructions for reassembly/recompose by the responsible pi-node (maybe the exit PI gateway). Authors suggest the analogy with protocols ruling Digital Internet interconnection (TCP/IP), proposing to keep track of a sort of "sequence number" allowing a smooth recomposition of pi-containers belonging to the same shipment. In addition, the transport layer provides services that ensure the faultless delivery of the shipment and manage the flows between the sending location and the corresponding destination. The shipping management activity is provided throughout all the transportation path and often is carried out by shipping company (intermediary companies dealing directly with clients). They manage receipt acknowledgment and provides tracking

services to clients in order to make them aware of the state of the shipment (tracking data are provided by lower layers – thanks to interconnection and communicational capacity of pi-movers and pi-containers).

Furthermore, transportation layer monitors the functioning of pi-containers and therefore guarantees that pi-containers are informed correctly and that they keep be able to communicate with other pi-constituents. This layer deals also with consolidation/deconsolidation of pi-containers in pi-hubs assuring an efficient unloading and loading of them.

- *Layer 3: Network Layer.* The most important tasks of the network layer include the provision of cross-network addresses (IP), the routing or creation and updating of routing tables and the fragmentation of data packets (Badach, Hoffmann and Knauer, 1997). This layer receives crucial data and information from the Transportation Layer such as: delivery orders, consolidation/deconsolidation orders with instruction to how reconnect fragmented shipments, shipping, and service constraints (like the maximum number of intermediate pi-nodes required by the typology of service required). This layer is in charge of updating routing tables and taking advantage of routing opportunities arising from the processed data regarding network status, pi-means/pi-nodes availability, roads, or pi-nodes congestion etc (received from the layer below, namely Link Layer).

  Furthermore, protocols managing cross-network communications are established and exploited. Different networks could be represented by different shipping companies with different address spaces. This would then be the task of the pi-node to mediate.
- *Layer 4: From Data Link Layer to Link Layer.* In order to prevent transmission errors and data loss, this layer contains functions for error detection, error correction and pi-constituents flow control. Indeed, thank to services provided by this layer, networks can rely on access to pi-means and pi-containers for data exchange. For example, pi-nodes can access to free capacity data about pi-means available to provide transportation service to shipment orders waiting to be shipped at nodes. Moreover, pi-movers can inform pi-nodes about road congestion and make them able to avoid routing pi-containers through those roads (flow control activities on links of the network).
- *Layer 1: Physical Layer.* After having received encapsulation, maintenance, loading, moving, sorting, storing, retrieving, and unloading orders from upper layers, the Physical Layer deals with carrying out physically these tasks. Therefore, here pi-

nodes manages pi-movers in the hubs, activities at entry/exit gates, pi-conveyors routing pi-containers from inbound gates to outbound ones. In addition to this, the physical encapsulation of products to ship in suitable pi-containers and the consolidation/deconsolidation activity is carried out at this layer. Following the analogy with Digital Internet, authors transpose "amplification" of data packets (within the DI context) into the refuelling process of pi-movers, pi-means.

The graphical result of the transposition carried out by this paper is shown in the following table.

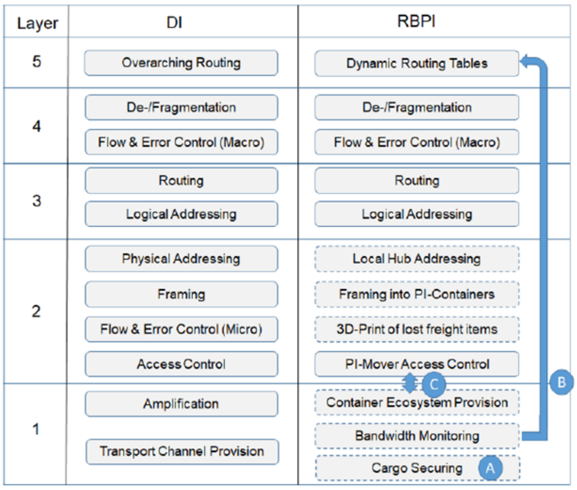

Figure 18 Artifact Framework for RBPI as a result of the Transformation

According to this paper, vehicle requirements are identified and highlighted by blue circles in the above figure. These requirements include automatic load securing (indicated by circle A), feedback on available capacities to dynamic routing tables (circle B), and optional power supply for containers with special treatment (circle C). The feedback loop allows freely available transport capacity information to be shared among hubs and this is made possible if vehicles possess knowledge of their load states or free capacities, which can be obtained through in-vehicle tracking systems or fleet management systems.

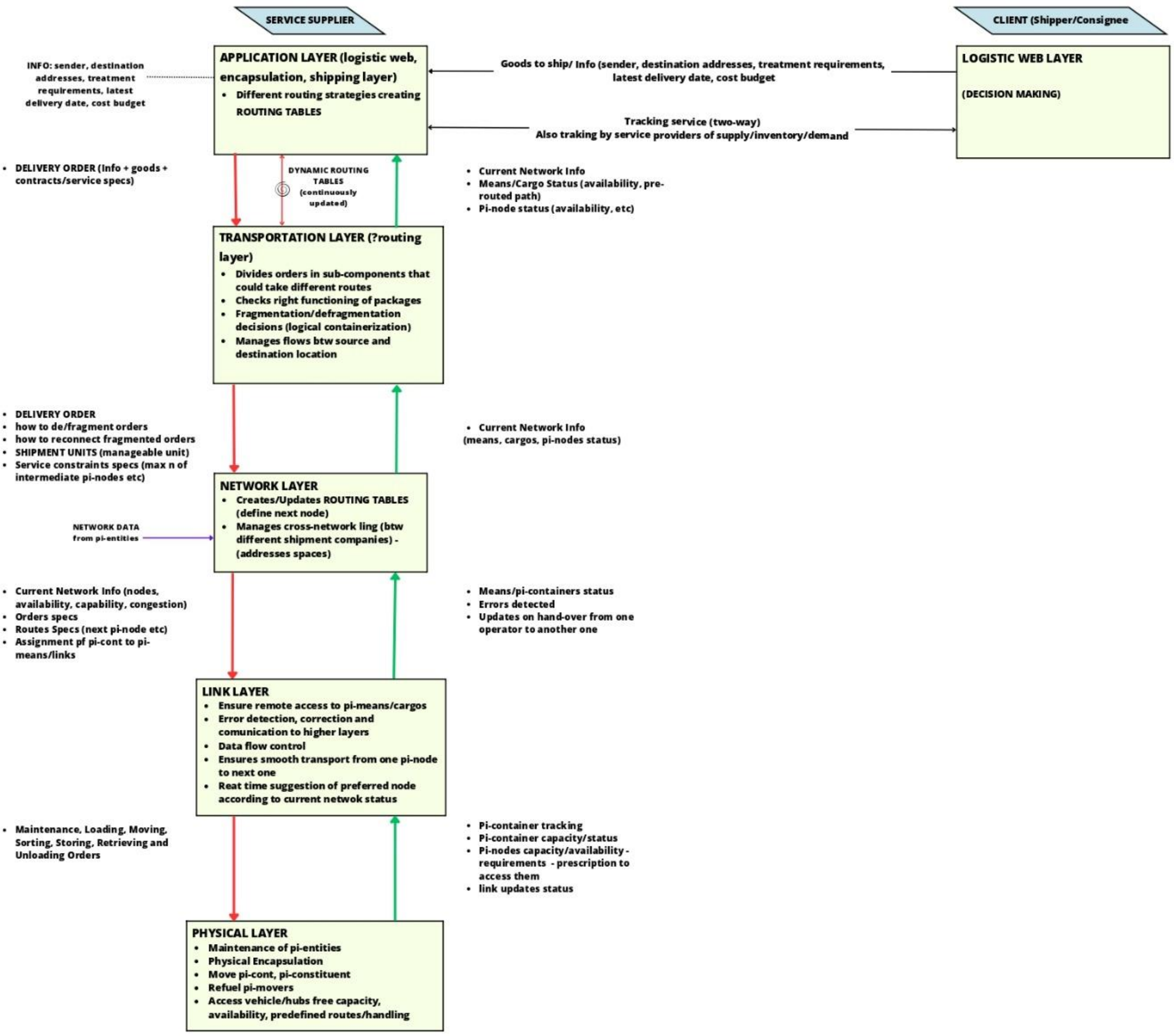

Figure 19 Physical Internet Conceptual Five Layers Model (Liesa et al., 2020) with new insights from (Kaup, Ludwig, & Franczyk, 2021)

A Dynamic Routing protocol with payments for the Physical Internet. A simulation with learning agents – Briand, Franklin, Lafkihi – 2022

Briand et al. (2022) addresses the difficulties in optimizing a dynamic routing system that needs to process a large number of loads within short timeframes. It emphasizes the importance of employing fast and user-friendly protocols, similar to those used in the Digital Internet, since complex optimization methods may not yield efficient routing services.

To tackle these challenges, the paper proposes a game theoretic approach consisting of an auctioning process at the core of the protocol. The primary objective of this protocol is to minimize the overall routing cost by incorporating concepts inspired by Digital Internet routers, such as administrative distance.

The final protocol involves three intelligent agents: shippers, nodes, and carriers. However, due to the complexity of their actions and interactions, a simulation-based approach is necessary. The shippers are assumed to exhibit simple behaviours, while the nodes and carriers employ a learning process. The simulation demonstrates the protocol's efficiency by significantly reducing total delivery costs and minimizing empty mileage.

Routing Protocol

The introduction of a user-friendly routing protocol by the authors is a significant contribution addressing the challenges of load transfer within a network. The protocol stands out for its incorporation of a fast and efficient auction process, which is crucial for optimizing the routing system. The auction process is specifically designed to be run whenever at a transport node both a load and a carrier are waiting for transportation. This process involves three key agents, namely shippers, transport nodes, and carriers. Shippers represent the client side, providing loads to be transported. Transport nodes serve as the intermediaries within the network, facilitating the transfer of loads between shippers and carriers. Carriers play a crucial role as the transportation providers, responsible for delivering the loads to their destinations. The auction protocol is reported below.

At designated start nodes, shippers initiate the process of generating loads and provide destination information to the nodes. When a load reaches a subsequent node, shippers can choose to participate in an auction by submitting a reserve price. In case the load remains unauctioned, shippers have the flexibility to adjust the reserve price or withdraw their participation.

Carriers have the responsibility of transporting loads of shippers. Upon reaching a node, carriers can decide whether to take part in the next auction by submitting bids for the available lanes connected to that node. If carriers lose an auction, they have the option to bid for another load or choose not to participate further. However, if carriers win, they are obliged to transport the load on the agreed lane, shipping requirements and price.

Nodes play a crucial role in facilitating the auctions. Whenever a load with a reserve price and a carrier with a bid coincide at a node, the nodes initiate an auction. After the auctions are completed, the nodes communicate the results, oversee payment transactions, and charge shippers for auction-related expenses and internal operational costs, including load handling within the node.

Nodes make informed decisions by considering the current context at the given node, taking into account accurate information and estimations of uncertain future costs to minimize the overall cost. These decisions may involve the utilization of complex statistical methods. In practical implementations, nodes may communicate with each other to indicate congestion, and the estimation methods employed may be more intricate. Designing the protocol, a crucial point to address is the design of weights used in the decision-making process to evaluate different lanes (links in the network) according to different factors that make them less or more suitable for that transfer.

The authors stress the significance of designing lane weights carefully to optimize routing efficiency. The objective is to reduce the total delivery cost by accurately estimating remaining costs at each node. Inspired by Digital Internet router protocols, the protocol aims to minimize overall expenses by considering present bid costs and future cost estimations. According to this paper, real-world implementation would involve complex statistical methods and communication among nodes (and other actors) to address congestion and provide more sophisticated estimations. In this regard, it is highlighted the requirement of a data sharing structure with two communication channels: one to disclose performance information while protecting privacy, and another to share relevant details like capacity constraints or disruptions.

Shippers induct new loads at various nodes in the network to start the process (it is assumed that the shipper is responsible for transporting the shipment to the induction point). These loads are meant to navigate through intermediate nodes toward the destination node. When a load is at a node which is not its destination, the node will ask the shipper for a reserve price and the carriers for bids. The node will then jointly select a next node and a carrier for transporting the load to the selected node by running an auction (preferred paths to the next node are defined the size of the lane weight penalty). The results of the auction are then communicated to the shipper and the carriers, so that the winning carrier starts her journey toward the next node, the shipper pays his charges to the auctioning node and the transportation fees to the winning carrier, and the losing carriers can decide to keep participating to auctions at this node or leave.

The authors describe their proposed protocol as "carrier agnostic," meaning that it does not make any assumptions about the identity of the carriers responsible for transporting the loads. This implies that the protocol can accommodate various types of carriers, such as third-party logistics (3PL) companies with network property rights or independent small carriers operating on smaller network links. Therefore, the protocol is designed to be flexible and adaptable to different carrier configurations. The authors draw a parallel between their approach and the way packets are routed in the Digital Internet. In the Digital Internet context, packets of data are exchanged between source and destination Internet Service Providers (ISPs), traversing networks owned by other ISPs. Similarly, in the proposed protocol, loads are transported through a network involving multiple carriers. This similarity highlights the concept of routing in both scenarios, where the focus is on efficiently directing packets or loads from their source to their destination, regardless of the specific carriers or networks involved in the intermediate stages. By adopting a carrier-agnostic approach, the proposed protocol aims to provide a flexible and adaptable solution that can accommodate different carrier arrangements. This flexibility is essential in real-world logistics scenarios where the carriers may vary in size, capabilities, and ownership structures. The protocol draws inspiration from the routing principles employed in the Digital Internet, leveraging the efficiency and effectiveness of routing mechanisms while adapting them to the domain of load transportation.

The protocol, just described, incorporates an auction process to enable dynamic interactions and negotiations among shippers, transport nodes, and carriers. This facilitates efficient load allocation and distribution across the network. The auction mechanism determines optimal prices and matches carriers with suitable loads, aiming to enhance the overall efficiency and effectiveness of the routing system. The integration of a user-friendly routing protocol with a fast and efficient auction process presents a promising approach to improving load transfer within a network. The protocol's effective interactions and load allocation have the potential to optimize routing operations and enhance the overall performance of the system.

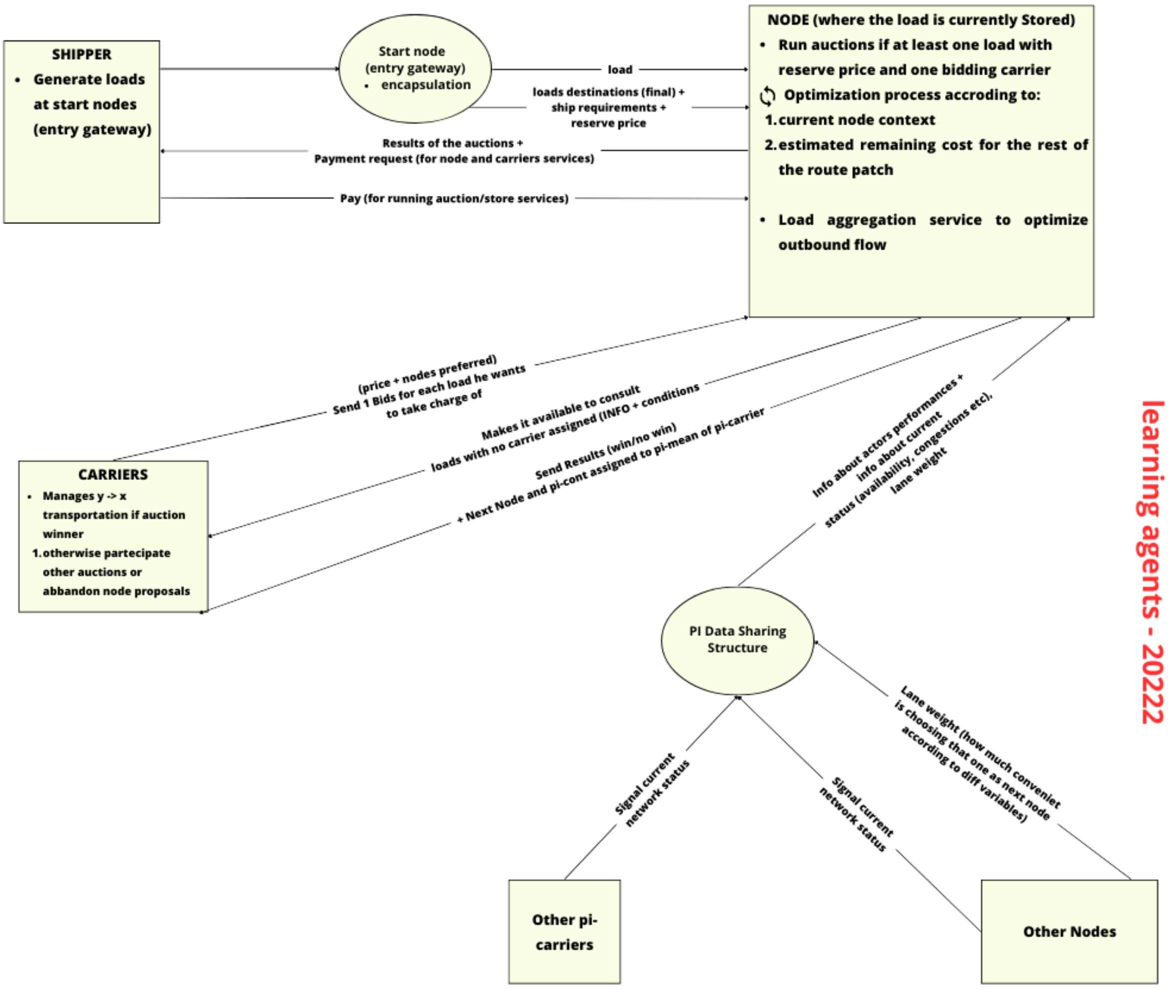

Figure 20 Protocols inferred from (Briand, Franklin, & Lafkihi, 2022 – circles refer to an unspecified shared data structure

4. Results

4.1 Kind of Messages

Starting from the previously identified research gap, we attempted to categorize the various essential processes involved in the functioning of a Physical Internet network into specific protocol categories, as independently as possible. This sort of categorization that we aimed to define was intended to facilitate the modelling of a comprehensive PI protocol system dividing it into these different and almost independent protocol categories and, as consequence, into specific types of messages exchange. This crucial data exchanges within the context of logistics processes, in the Physical Internet perspective, would enable various actors (Pi-shipper, Pi-carrier, Pi-node) to communicate efficiently, just complying with those protocols. The macro-categories identified in the scope of this thesis are as follows:

- **Routing/Composition-Decomposition of PI-Containers:** protocols and data exchange necessary to enable the network (PI-node or its counterpart) to compose and decompose containers among themselves for efficiency purposes during loading and unloading activities, and ultimately to correctly route the containers within the PI, through different nodes and hubs.
- **Contract Establishment/ Node/Carrier Assignment:** protocols and data exchange required for creating an "instance of shipment" and the subsequent sending of work order to different service providers. Specifically, particular attention is devoted to the assignment of that shipping order to a PI-carrier, often carried out through an auction-based process.
- **Single Node Protocols:** protocols and data exchange necessary to an individual node for interacting with other actors of PI and for them to interact with the node to carry out activities within the node.
- **Encapsulation:** protocols and data exchange required for optimal encapsulation of goods to be managed within the PI in standard containers according to pi-shippers' requirements.
- **Network Architecture/Structure:** architecture of the network of networks (autonomous systems, border nodes, nodes facilitating communication between different "autonomous" networks, etc.) and protocols ruling the entrance of any pi-actors providing pi-services (pi-carriers, pi-nodes, pi-hubs, etc) within a specific network.

After the definition of these five categories for message exchange we proceeded presenting the most relevant insights from the literature on the PI protocols categorizing the 15 publications analysed based on the five typologies defined above. In Table 23, available for consultation below, it is presented a Boolean table connecting papers reviewed and protocols' categories they address in order to facilitate the critical analysis comprehension.

Routing/Composition-decomposition of pi-containers

Several authors have published and discussed on the conception of routing protocols in the context of Physical Internet. For instance, Montreuil, Ballot and Fontane (2012) proposes a seven-layer model able to outline how logistic services could be arranged within and across these layers. This model provides for predefined routes computed at the start node and routing opportunities to exploit in intermediate pi-nodes according to shipping contracts (destinations, time attributes, priority specs), network status (segment, nodes) and carrier readiness and availability (service capability, capacity, performance, means status). Moreover, the paper highlights how composition and decomposition of pi-containers (carried out thanks to interlocking mechanisms in the different pi-nodes along the path) allows optimal utilization of services (pi-means) and provides different factors to consider in order to optimize this process including future states of pi-constituents (next nodes, future shipping disturbances etc). Following this view, Sarraj et al. (2014) adds an important insight into the discussion introducing a distribute protocol alghoritm optimizing the consolidation of pi-containers solving the well-known bin-packing problem with heuristic approaches, that require a specific protocol to be executed. A particular stress is devoted to the dynamic interdependence between routing and consolidation protocols, both requiring open monitoring properties of PI and thus exploiting upcoming flows of data. Therefore, authors explain how this seamless data exchange needs to be supported by a sustainable and resilient digital infrastructure in order to allow dynamic best-path computing.

Colin et al. (2016) proposes a seven-layer model for logistic services in the Physical Internet, alternative to the one by Montreuil, Ballot and Fontane (2012). They define physical objects in different layers when they first appear and not just in the lowest layer. One of these layers is dedicated to routing services (network layer). To this purpose, authors theorize an intense data exchange required to carry out routing service according to which a lot of data are needed: shipping contracts, network status, carrier readiness and availability. For this reason, Physical Internet, according to Colin et al. (2016), relies on this layer for data structure management (essential to best path computing) and recommend designing it as decentralized (in different nodes/actors of the chains) or centralized (at least at network level).

The first appearance of routing tables in the context of PI is in the paper by Sarraj et al. (2012). They theorize a routing protocol defining routing tables at each node to determine best next node based on shipping requirements in input. These routing tables are then regularly updated to reflect changes in network topology, available paths, and network conditions. The protocol proposed here empowers nodes to utilize flow understanding and future state estimation to optimize routing protocols/tables between nodes. This possibility makes it crucial an information exchange infrastructure able to gather information about past and current network status in order to make nodes able to process those data and provide future state-informed routes.

Another research work providing a protocol for routing pi-containers is the one by Gontara, Bounfaied and Korbaa (2018). Differently from previous ones, here authors define a well-structured PI-BGP Protocol for routing pi-containers able to dynamically adapt according to unpredictable events (delays due to unavailability of routes or trucks, road congestion etc). Moreover, this paper is the first among those reviewed that shifts its perspective on the routing problem, considering vehicles as links with different states rather than flows (semi-defined segment where periodically specific means operate), and emphasizing the cruciality of pi-containers as primary focus for dynamic routing within the Physical Internet.

Kaup et al. (2021) presents a five-layer model for logistic services proposing different routing strategies (with different peculiar functioning) creating and updating dynamically routing tables such as RIP (Routing Information Protocol), OSPF (Open Shortest Path Information First) and BGP (Border Gateway Protocol). These protocols necessitate substantial data collection at pi-nodes that offer routing services. This includes details like delivery orders, shipping constraints, network status, pi-means/pi-nodes availability, congestion, etc. Such data acquisition is feasible when networks are designed to be open and global, enabling actors to access specific information from others, even across different networks, and contribute essential data about their own operations.

Contract establishment/node-carrier assignment

Montreuil, Meller and Ballot (2012) briefly outlines different-levels protocols. Specifically, among the so called "higher-level protocols" authors locate the pi-contracting protocols, the ones required to establish standardized pi-contracts for logistics services within the Physical Internet. Authors highlight the possibility to extend existing International Commercial Terms (INCOTERMS) and to adapt them to Physical Internet.

As far as the publication by Montreuil, Ballot and Fontane (2012) is concerned, the same seven-layer model discussed in the previous paragraph identifies the first layer (Logistic Web Layer) as the one designated to allow the creation of the "instances" of shipment thanks to a bulk of data required in input from the shipper/sender. In addition, here dynamic decisions regarding product supply, production, distribution, and transportation take place and therefore, according to authors proposition, any sort of contract establishment with their protocols are managed and conceptualized.

On the other side, as part of the seven-layer model for logistic services proposed by Colin et al. (2016), this paper makes a detailed description of the data exchange required to establish any type of contracts (production, supply, distribution, shipping contracts) between parties in the context of Physical Internet. Specifically, the data exchange involves purchase orders, delivery instructions (sourcing location, destination, possible cold chain requirements, delivery time), INCOTERM specifications etc. Most of these data are delivered from clients/shippers to pi-nodes or anyone managing data enabling products to ship enter the Physical Internet networks (once encapsulated).

Lafkihi, Pan and Ballot (2019) detects and design a set of protocols going to regulate and mediate interactions between actors in the PI-like network. Specifically, Lafkihi et al. (2019) provides an incentive mechanism equipped with an auction-based optimization model alongside the rules for collaborative transport request assignment to pi-carriers and related due payments. On top of this, a protocol to let carriers sub-contract their transport orders to other carriers in an economically sustainable way is proposed.

Briand et al. (2022) provide a fast and efficient auction protocol designed to facilitate transport request assignment t pi-carriers whenever both a container and a carrier are waiting for transportation. They model three agents – protocols able to rule on interaction between Carriers (with their pi-means), Shippers (with their pi-carriers) and Transport Nodes (acting as auctioneer). This auction mechanism proves to determine optimal prices and matches (pi-carriers with pi-containers) improving the process in terms of efficiency and effectiveness of the routing system.

Single nodes protocols

Three reports present detailed functional design for Physical Internet (PI) facilities. Montreuil et al. (2012b) describe a road-based transit center functioning like an internet switch. Ballot et al. (2013) outlines a road-rail hub with scheduled rail transport, unlike trucks that leave once filled. Montreuil et al. (2013) elaborate on the design of a unimodal road-based crossdocking hub. These publications offer insights into different PI facility designs, reflecting the network's adaptability and efficiency-enhancing strategies for various transportation modes.

Chargui et al. (2019) addresses protocols that manages Rail-Road PI-hub cross-docking processes defining functionalities and layout. With the purpose to optimize cross-docking activities, the protocols proposed are intended to minimize both energy consumption and outbound truck costs assuming a multi-objective approach. A clear description of the data required by the hub for truck scheduling is provided and in turn resulting output variables are presented.

Patch et al. (2014) offer a grouping protocol (consolidation) for pi-containers at node-level and demonstrate their effectiveness. It is able to optimize the saturation of transportation means consolidating multiple small pi-containers in front of the truck before loading and treating them as a single composite pi-container during the loading process. These protocols provide for smart pi-containers capable to communicate with each other and process info in input to perform micro-decision-making activities.

Encapsulation

The PI foundational paper by Montreuil, Meller and Ballot (2012) defines the pi-container as fundamental shipping unit to manage within the Physical Internet. Therefore, encapsulation concept is recognized by the whole literature as the logical entry-gateway of the PI, what enable different freights and product to flow across nodes and networks thanks to pi-containers standardization.

The encapsulation process is clarified accurately in Montreuil, Ballot and Fontane (2012). It dedicates two different layers (out of seven total layers) of the logistics service at managing efficient encapsulation of product to ship in uniquely identified pi-containers before accessing PI networks (PI entry gateways). Protocols of data exchange are proposed in order to optimize the process and therefore assign the best-fit standardized pi-container among those accepted and certified by the network of networks.

The papers by Sarraj et al. (2014) and Patch et al. (2014) addresses the so called "goods containerisation protocol" outlining the process of grouping products for shipment within the Physical Internet. According to authors this protocol becomes essential in assigning products to "best" fitting PI-containers according to several shipment features provided by the shipper such as size, weight, customer preferences and requirements about the shipment, time-related issues.

Network architecture/structure

In Sarraj et al. (2012) authors dig into several analogies between internet networks and logistics service networks transposing architectural elements of Digital Internet into the Physical Internet context. Indeed, they propose a network architecture for the Physical Internet based on different PI-Autonomous Logistic Networks (just like Autonomous Systems in Digital Internet), each independently managed by a single operator, capable to manage and define a network, interconnected to others through the so called "border nodes" (nodes able to interconnect two heterogeneous PI-Autonomous Logistic Networks). This paper argue that this autonomous network has to be in charge of managing protocols to communicate with other networks and within the same network.

The paper by Gontara, Bounfaied and Korbaa (2018) resumes the concept of Physical Internet Autonomous Systems in the context of PI nodes architecture. Indeed, they reaffirm the importance of treating contemporary Logistic Service Providers (LSPs) as Physical internet Autonomous Systems (PI-AS), each operating with its specific routing protocols, yet it is imperative to uphold shared standards. This necessitates the establishment of protocols and standards that facilitate effective communication between distinct PI-AS, enabling seamless transit of pi-containers across PI-AS boundaries to reach their destinations.

YEAR	PAPERS NAME	AUTHORS	Routing/Compostion-decomposition of pi-containers	Contract establishment/Auction based carrier assignment	Single nodes protocols	Encapsulation	Standard Smart Interfaces	Network architecture/structure
2012	An Open Logistics Interconnection Model for the Physical Internet	B. Montreuil, E. Ballot, F. Fontane	x	x		x	x	
2012	Analogies Between Internet Networks and Logistics Service Networks: Challenges Involvdd in the Interconnection	R. Sarraj, E. Ballot, S. Pan, B. Montreuil	x					x
2012	Functional Design of Physical Internet Facilities: A Road-Based Crossdocking Hub	B. Montreuil, R. D. Meller, C. Thivierge, Z. Montreuil			x		x	
2012	Functional Design of Physical Internet Facilities: A Road-Based Transit Center	B. Montreuil, R. D. Meller, C. Thivierge, Z. Montreuil			x			
2012	Physical Internet Foundations	B. Montreuil, R. D. Meller, E. Ballot		x		x	x	
2013	Functional Design of Physical Internet Facilities: A Road-Rail Hub	E. Ballot, B. Montreuil, C. Thivierge			x			
2014	Interconnected Logistic Networks and Protocols: simulation-based efficiency assessment	R. Sarraj, E. Ballot, S. Pan, D. Hakimi, B. Montreuil	x			x		
2014	Routing Management in Physical Internet Crossdocking Hubs: Study of Grouping Strategies for Truck Loading	C. Pach, Y. Sallez, T. Berger, T. Bonte, D. Trentesaux, B. Montreuil			x	x		
2016	A Proposal for an Open Logistics Interconnection Reference Model for a Physical Internet	J. Colin, H. Mathieu, M. Nakechbandi	x	x				
2018	Routing the PI-Containers in the Physical internet using the PI-BGP Protocol	S. Gontara, A. Bounfaied, O. Korbaa	x					x
2019	Multi-Objective Sustainable Truck Scheduling in a Rail-Road Physical Internet Cross-Docking Hub Considering Energy Consumption	T. Chargui, A. Bekrar, M. Reghioui, D. Trentesaux			x			
2019	Rule-based incentive mechanism design for a decentralized collaborative transport networl	Marlam Lafkihi, Shenle Pan, Eric Balot		x				
2019	Toward the Internet of Things for Physical Internet: Perspectives and Challenges	H. Tran-Dang, N. Krommenacker, P. Charpentier, D. Kim					x	
2021	Framework Artifact for the Road-Based Physical Internet based on Internet Protocols	S. Kaup, A. Ludwig, B. Franczyk	x					
2021	The Physical Internet in the Era of Digital Transformation: Perspectives and Open Issues	H. Tran-Dang, D. Kim					x	
2022	A Dynamic Routing Protocol with Payments for the Physical Internet: A simulation with learning agents	M. Briand, R. Franklin, M. Lafkihi		x				

Table 4 Boolean table connecting papers reviewed and themes they address regarding protocols and data exchange

4.2 Exchange System

Through the study of literature on the Physical Internet and the research work carried out on the communication protocols that enable the functioning of logistics processes from a Physical Internet perspective, we have concluded that a point-to-point messaging system was not sufficient to support the universal interconnection that the Physical Internet theoretically promises. Although the literature does not sufficiently and comprehensively address this topic, there are numerous scientific articles (analyzed in this thesis) that refer to a kind of platform with an open data structure (often referred to as 'digital middleware platforms') that allows various actors in the Physical Internet to share information with the network and access specific information that the network possesses, overcoming the need for point-to-point communication, at least for most of the logistics processes. Montreuil, Meller, Ballor (2012) first wrote about this digital middleware platform as a means to facilitate various types of interactions and information exchange, including human-human, human-agent, agent-agent interactions. Furthermore, in Montreuil, Ballot, Fontane (2012), the authors refer to the Logistic Web Layer (part of the 7-layer structure, a model for the Physical Internet) as an open window to the Physical Internet through which users (logistics actors) can have real-time visibility (if authorized according to protocols) into the performance levels of other service providers, the states of various PI constituents (pi-means, pi-containers, pi-nodes, pi-links, etc.) of interest, pending shipping requests, and much more. On the other hand, there are also publications that propose specific models for some PI processes, often well-structured, based on point-to-point communication. Specifically, I refer mainly to the processes of managing activities within individual nodes and the information exchanges that occur between individual nodes and the physically interfacing actors. In Montreuil, Meller, Thivierge, Montreuil (2012), it is clear how the management of unloading, loading, and addressing of pi-trucks (or any pi-means) is supported by close communication between pi-carriers and reference pi-nodes.

Therefore, starting with the awareness that our proposed model could not do without a decentralized and as open as possible data exchange structure, we thought of a hybrid message exchange system based on Publish-Subscribe (Pub/Sub) systems and point-to-point communication where it is required. A Publish-Subscribe (Pub/Sub) system is a messaging pattern used in distributed systems and software architecture to enable communication between different components or systems without them needing to know about each other. It is a form of asynchronous messaging where senders (publishers) of messages do not specifically address receivers (subscribers). Instead, they publish messages to one or more channels or topics, and subscribers express interest in receiving messages from specific channels or topics. When a message is published to a channel or topic, all interested subscribers receive a copy of the message.

The achievement of universal interconnectivity within the Physical Internet is crucial in order to allow for efficient communication and interaction among all components and entities within the Physical Internet. In this regard, we thought about the Pub/Sub system as capable of making universal interconnectivity possible in this context, providing a sustainable and resilient digital infrastructure supporting real-time data exchange. Indeed, Pub/Sub systems, being suited for building scalable, decoupled, and efficient distributed systems, can be extremely efficient when it comes to handling the complexities of the logistics services and the new challenges PI poses.

The Pub/Sub messaging pattern is founded on the following three cornerstones: publishers, subscribers, and Channels/Topics. A publisher is responsible for creating and sending messages to the Pub/Sub system. Publishers produce messages and attach them to specific channels or topics. A subscriber expresses interest in receiving messages from one or more channels or topics. Subscribers receive messages that match their interests. Transposing these concepts into the context of the Physical Internet, the publisher and the subscriber will be any PI-actor sharing data with the network or any PI-actor, being interested in specific data, decide to receive and access them by subscribing to specific topics. Instead, a channel or topic is a logical channel for messages. Publishers publish messages to specific channels or topics, and subscribers subscribe to these channels or topics to receive messages. Channels or topics are used to categorize and organize messages, making it easier for subscribers to express their interest in specific types of messages and for publishers to target their messages to specific audiences. For this reason, we deemed Pub/Sub systems as the most suitable to address PI data exchange challenges, exploiting the categorization we proposed in the previous pages.

This thesis aims to outline a protocol model that uses Pub/Sub logic to make information exchange and data sharing possible among different actors within the Physical Internet. Therefore, below, we propose some Channels/Topics we reckon essential to support Physical Internet logistics (reassumed in table 5).

Pub/Sub Topics proposed

PARAMETRIC CHANNEL	PUBLISHERS	SUBSCRIBERS
#/admission-requirement/<pi-entities>/<ASnetwork>/<zone>	PI-AS Network Manager	Potential PI-actors interested in gaining access to a specific network (and zone) to offer logistics services
#/<operating-pi-entity>/<ASnetwork>/<zone>	PI-AS Network Manager	Pi-actors interested to the operating pi-entity in a specific network and zone
#/auctions/startnodeselection/<ASnetwork>/<zone>	Pi-shippers interested in entrusting the package to an initial node (entry-gateway of PI) in a specific network and zone	All pi-nodes providing encapsulation and services as start-nodes in a specific network and zone
#/state/<pi-constituents>/<unique-identifier-pi-constituents>	Smart pi-entities with tracking, monitoring, and data-sharing capabilities	Pi-shippers interested in monitoring the shipment (on behalf of clients or providing tracking services to clients), pi-nodes interested in understanding the state of pi-containers flowing through their facility, pi-links and pi-nodes status in order to compute optimal routes, pi-actors interested to know the status of a specific pi-entity
#/auctions/pi-containers-transportations/<ASnetwork>/<zone>	Pi-nodes publishing their request of transportation of pi-containers that need to be transmitted to the next pi-node	Pi-carriers interested to take charge of new pi-containers to transport

Table 5 - Parametric channels proposed

The first Pub/Sub topic we introduce is aimed at supporting the registration process for potential logistic service providers into the Physical Internet network. For example, if a node or carrier (not yet part of a PI network) wishes to join a specific PI network in a particular zone, they have the option to access the incoming certification process through the following Pub/Sub channel:

Topic Pub/Sub (parametric):

#/admission-requirement/<pi-entities>/<ASnetwork>/<zone>

Unique publisher: PI-AS Network Manager (pi-actor managing an autonomous network – interconnected to other networks)

Subscribers: potential PI-actors interested in gaining access to a network to offer logistics services

The topic (proposed here in a parametric form) in this case primarily denotes the process that supports, within the Physical Internet framework, specifically the incoming certification of new entities of any kind (pi-node, pi-carrier, pi-shipper, pi-means, etc). Additionally, the second hierarchical level indicates the reference network to which the entry request is intended. Following the network architecture proposed in Sarraj, Rochdi, Ballot, Eric, Pan, Shenle, Montreuil, Benoit (2012), the network of networks in the Physical Internet would consist of various Physical Internet Autonomous Logistic Networks (similar to the Digital

Internet), large networks interconnected with all others (by border nodes), each independently managed by a single actor. In our model, autonomous systems networks are themselves divided into zones. These actors managing these large networks not only ensure that their network can communicate and interconnect with others but also oversee the multi-level certification process of containers, handling systems, vehicles, devices, platforms, ports, hubs, roads, protocols, processes, and more. It ensures that the various components and entities within its network meet the necessary standards to carry out logistics services within their "borders" and are capable of collaborating with other networks.

Therefore, in the proposed Pub/Sub Topics (varying for the requesting pi-entity, network, and reference zone), it is indicated that the sole publisher of the topic is a kind of PI-AS Network Manager, naturally interested in new potential pi-actors within their network and in informing them of the entry requirements for the same. On the other hand, the subscriber-type for these topics will be all potential pi-actors interested in the standards to be followed for entry.

Indeed, within these channels, the PI-AS Network Manager publishes and updates the channel with the entry requirements for various pi-actors (protocols to adhere to, node design characteristics, technologies needed to ensure the interconnection required by the PI). Any structure/organization that wishes to become part of the network subscribes to the relevant channel for their pi-entity type. So, the potential pi-entity becomes a subscriber to the reference channel. After verifying the requirements and perhaps aligning their structure/organization with them, the pi-entity resorts to traditional point-to-point communication to submit the entry request. The pi-entity will attach to the registration request all the information regarding its infrastructure/organization and the services it could provide to the network.

Another Pub/Sub Topic we want to propose is the one capable to inform the entire network about the different pi-actors operating in a precise AS network and zone. The is the following:

Topic Pub/Sub (parametric):

#/<operating-pi-entity>/<ASnetwork>/<zone>

Publishers: PI-AS Network Manager

Subscribers: all pi-actors interested to the operating pi-entity in specific Networks and Zone

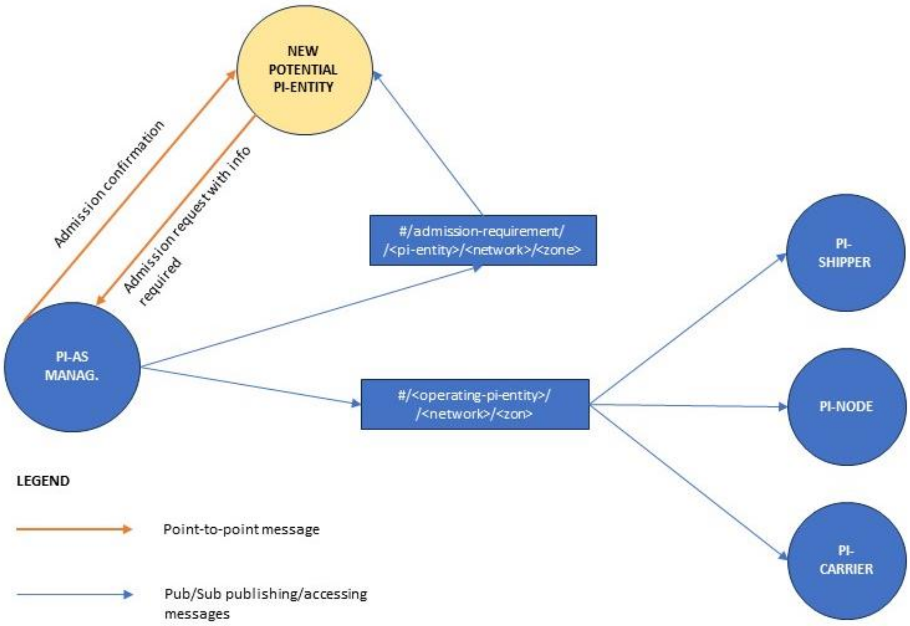

Figure 21 Hybrid Data Exchange System with both Pub/Sub Topics and Point-to-point exchange - New entities inscription to an AS Network

A customer who wants to send a packet through a Physical Internet network has to turn to a pi-shipper that will manage and monitor the entire logistics process. However, the good to be shipped has to be handed over to a Pi-entry-gateway in order to be encapsulated and routed through the PI-network. With this purpose, the pi-entry-gateway selection is carried out through an auction process that determines the best node capable of offering the required services at the best price. The choice of the Pi-entry gateway by the Pi-shipper is primarily done through the use of the Pub/Sub system, specifically via the following topic:

Topic Pub/Sub (parametric):

#/auctions/startnodeselection/<ASnetwork>/<zone>

Publishers: pi-shippers interested in entrusting the package to an initial node (located in network A, Zone 1) capable of encapsulating the goods and routing them to the destination (through intermediate nodes).

Subscribers: all pi-nodes providing encapsulation and services as start-nodes in networkA and Zone1

In this channel, pi-shippers interested in entrusting the package to an initial node (pi-entry-gateway located in the network and the reference zone) publish requests for the pickup of packages within the channel. These requests include information related to the shipments being requested: sender and destination addresses, treatment requirements, latest delivery date. Based on the information provided by shippers, different pi-nodes (capable of providing the required services) can choose whether to participate in the auction for available shipments or not.

A crucial series of Pub/Sub Topic we propose are those where most of pi-constituents (pi-containers, pi-means, pi-nodes etc), equipped with tracking, monitoring devices able to communicate data in real-time, update their state (position, work load, availability, possible future states etc) and made them available to access by the entire network (if authorized). This data are crucial for many pi-actors in order to facilitate and optimize their logistics processes and decision-making. The parametric Pub/Sub Topic is the following:

Topic Pub/Sub (parametric):

#/state/<pi-constituents>/<unique-identifier-pi-constituents>

Publishers: smart pi-constituent with tracking, monitoring, and data-sharing capabilities or pi-actors responsible for the pi-constituents.

Subscribers: pi-shippers (and senders) interested in monitoring the shipment of pi-containers throughout the entire journey (on behalf of clients or providing tracking services to clients) pi-nodes interested in understanding the state of pi-containers flowing through their facility or pi-links and pi-nodes status in order to compute optimal routes.

The last Pub/Sub Topic we want to present is the one supporting the pi-carrier assignment when the next optimal pi-node has been designated and the transport of the pi-container has to be assigned to some pi-carrier. For the pi-carrier assignment, once again, the pi-node uses a Pub/Sub Topic in which to publish a transport request, providing all the details of the pi-container.

Topic Pub/Sub (parametric):

#/auctions/pi-containers-transportations/<ASnetwork>/<zone>

Publishers: pi-nodes publishing their request of transportation of pi-containers that need to be transmitted to the next pi-node

Subscribers: pi-carriers interested to take charge of new pi-containers to transport

Once pi-nodes publish delivery requests with related information (destination, time-related info, freight requirements) all pi-carriers must carefully assess the available requests from the pool to determine which delivery requests align best with their capabilities.

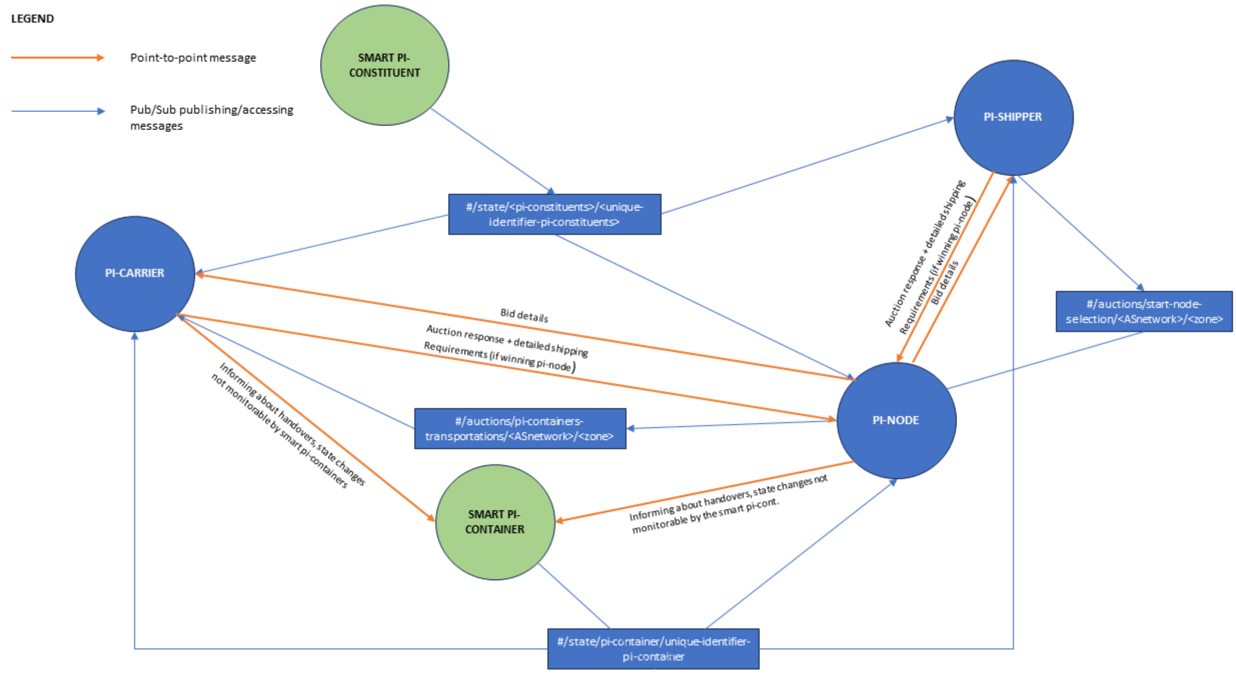

Figure 22 Hybrid Data Exchange System with both Pub/Sub Topics and Point-to-point exchange - Typical logistics processes in Physical Internet

5. Use cases

In this chapter, this thesis will present several use cases to depict potential typical scenarios of the Physical Internet and to demonstrate the effectiveness of the message and information exchange model proposed in the previous chapter. Below are the various use cases.

Data exchange for a node to join a PI-AS network

For a node to become part of a PI-AS network (managed by a PI-AS Network Manager), it must adhere to certain protocols and specific standards for that network that enable effective collaboration with other pi-actors in the network and the provision of logistics services. These protocols and standards refer not only to a series of logistics processes to adhere to but also to specific requirements regarding the structure (in this case, of the pi-node) that is preparing to offer logistics services within a Physical Internet network. In this case, the "structural" requirements for a pi-node could include: the area of the pi-node site and facility, the number of inbound and outbound gates, the number of docks, the number of π-containers that can be processed concurrently within the hub facility, the possession of a series of hardware and software devices capable of supporting Physical Internet processes and, most importantly, efficiently using the data exchange system. Additionally, it is important that the pi-node is suitable for handling pi-containers with specific designs, ensuring that the pi-conveyors and pi-means working within the node are compatible with the pi-containers they handle.

In this regard, so that the node N (an actor in our use case) wishing to join the network is aware of the minimum requirements for entry, the PI-AS Network Manager publishes these requirements on a Pub/Sub channel/topic and updates them in case there are innovations in the protocols and standards to follow. The relevant Pub/Sub Topic in our use case is:

#/admission-requirement/pi-nodes/networkA/District1

Unique publisher: PI-AS Network Manager of networkA (pi-actor managing the autonomous network called "networkA"– interconnected to other networks)

Subscribers: pi-nodes wishing to become part of network A in district 1. In our use case, pi-node N will be a subscriber to this Pub/Sub Topic.

After verifying the requirements and perhaps aligning their structure/organization with them, pi-node N resorts to traditional point-to-point communication to submit the entry request to the PI-AS Network Manager of network A (actor of our use case). The pi-node will attach to the registration request all the information regarding its infrastructure/organization and the services it could provide to the network.

Once the entry request is submitted, the PI-AS Network Manager will scrutinize the data provided by the pi-node to verify if they align with the essential requirements and protocols for joining network A. To communicate the decision of admitting or rejecting the requesting pi-node N to the network, a simple point-to-point communication is used. In the affirmative case, the PI-AS Network Manager will update the list of actual operating pi-nodes in the network A and district 1on the following channel:

#/operating-pi-nodes/networkA/district1

Publishers: PI-AS Network Manager of network A

Subscribers: all pi-actors interested to know operating pi-nodes in network A and district 1

Furthermore, the PI-AS Network Manager will enable the newly admitted pi-node A to become a publisher or subscriber (depending on their role) of specific Pub/Sub topics (for accessing pi-entity states, publishing auctions for carrier assignment etc) so that they can become fully operational and collaborate within the network to provide logistics services.

Start pi-node selection for a good to ship

A customer C wants to ship a package within the Physical Internet circuit and turns to a pi-shipper P (an intermediary organization between the customer and the Physical Internet network, which can also be the same organization that controls a certain AS network or provides pi-node services). In the role of a pi-shipper, this organization will monitor the entire logistics process and will be directly responsible to the customer for the entire logistics service it provides (as the customer will pay for the entire service). For these reasons, we assume that pi-shipper P represents the interests of the customer, allowing us to consider the two actors as one.

The goods to be shipped are entrusted to the Pi-shipper along with all the information regarding the requested transport (sender, destination addresses, treatment requirements, latest delivery date, cost budget). Subsequently, the goods (accompanied by the relevant shipping information) are handed over to a Pi-entry gateway (the starting pi-node where encapsulation and initial routing services are provided) near the location where customer C delivered the package to pi-shipper P (Network A, District 1). This handover process occurs through an auction process that determines the best node capable of offering the required services at the best price.

The choice of the Pi-entry gateway by Pi-shipper P primarily occurs through the use of the Pub/Sub system, specifically through the following topic.

#/auctions/startnodeselection/networkA/District1

Publishers: Pi-shipper P interested in entrusting the package to an initial node (located in Network A, District 1) capable of encapsulating the goods and routing them to the destination (through intermediate nodes).

Subscribers: all pi-nodes providing encapsulation and services as start-nodes in network A and district 1

In this channel, pi-shipper P will publish the request for the pickup of the package. This request will include information regarding the recipient's address, treatment requirements for the goods, the latest delivery date, etc. According to information made available by shippers, different pi-nodes (capable to provide services required) can choose to participate or not to the auction for shipments available. Entry-gateway pi-nodes will carefully assess the available requests from the pool (made available in the channel) to determine which delivery requests align best with their capabilities. The factors (no related to price of course) regulating this process of decision making can be route feasibility, storing capacity, pi-containers availability etc.

After this choice, pi-nodes have to finalize their optimal bidding strategy coupling the chosen requests to bid for and the price to submit to maximise their profits. Once different pi-nodes (willing to bid) provide data about their facility and services to the pi-shipper and bidding price, an auction is run (out of the perimeter of Pub/Sub system) and the node offering the best bid both in economic and service quality terms will win the auction and take charge of the shipment. The pi-shipper then disseminates the results to the losing pi-nodes while providing detailed information to the winning one (pi-node N).

Encapsulation of the good to ship in a pi-container and activation of pi-container's smart features

After having received shipment requirements from the pi-shipper P, the pi-node N (entry-gateway) will encapsulate the good choosing the pi-container typology that fits the best according to: size, weight, freight-integrity preservation requirements and other attributes of the good to ship that can trigger a special treatment (all detailed information received from the shipper via point-to-point communication).

After being awarded the transportation of the freight and performed the encapsulation process, the pi-node creates an instance of shipment that will be monitored and updated throughout all the life cycle of shipment. Once the freight enters in the Physical Internet, the pi-container becomes the fundamental shipping unit to manage. Therefore, the chosen pi-container T is equipped with tracking, monitoring devices able to communicate data in real-time and is coupled with a unique identifier with the purpose of allowing any customer or stakeholder to access real-time information (position, status of equipment, route it is following, next pi-nodes, etc) thanks to applications enabled by IoT. Indeed, it will be possible for pi-containers (with active role) to share important information about its state, position with different interested stakeholders. In this dedicated channel the smart pi-container will share with all stakeholders all essential data to manage that pi-container shipment: the UUID (Universal Unique IDentifier) of the pi-container, its size, its weight (as loaded by the goods), the fragility of the contents (useful for handling it correctly), the possible perishability of the content (and consequent need for cold storage, for example) or the need for use of special environment (cold-chain), routing data (next nodes, established route), sender and receiver identity, source address where goods have been sent, description of goods, time window for the delivery etc.

With this purpose, it is crucial the use of the following Pub/Sub Topic:

#/state/pi-container/unique-identifier-pi-container

Publishers: smart pi-container T with tracking, monitoring, and data-sharing capabilities

Subscribers: pi-shippers (and senders) interested in monitoring the shipment throughout the entire journey pi-nodes interested in understanding the state of pi-container P flowing through their facility and all other pi-actors will come into contact with that pi-container.

The access (subscription) is restricted to pi-actors involved in the shipment process and therefore, once an actor is in charge of providing a logistics service for pi-container P he's admitted to subscribe to this channel. Moreover, when it comes to signal to the network some change of state, problems or handovers (not monitored automatically by the pi-container) the pi-actor handling the pi-container has to "inform" it about those circumstances in order to let the pi-container inform the network through the Pub/Sub Topic discussed above.

Best-path selection updating "routing tables"

Once the product to be shipped is encapsulated in a dedicated pi-container, the pi-node must calculate an initial route. As we discussed in the previous chapter, to determine the best path for a pi-container, the pi-node relies on specific "routing tables" that are dynamically created and updated. Therefore, pi-node N will ensure that its routing tables are adjusted to accommodate service updates, incoming flows, network disturbances, and the readiness of potential next pi-nodes. In our use case, pi-node N will access the following Topic Pub/Sub in order to update its routing tables:

#/state/link/<unique-identifier-pi-links>

Publishers: pi-carriers's devices installed on pi-trucks monitoring and sharing traffic data about pi-links (roads linking two nodes)

Subscribers: pi-nodes interested to link congestion in order to update routing tables and therefore also pi-node P

This Pub/Sub topic is presented here in parametric format to highlight how pi-node P will go to access data about traffic and flows of all candidate pi-links between the actual pi-node P and the destination.

Topic Pub/Sub:

#/state/pi-node/<unique-identifier-pi-node >

Publishers: pi-nodes publishing their status (readiness to handle, retain and re-route pi-containers)

Subscribers: pi-nodes interested to update routing tables according to real-time data provided by potential next pi-nodes and therefore also pi-node N.

By accessing these types of Pub/Sub Topics and processing data with specific algorithms, pi-node is capable of updating their routing tables in real-time. Once the routing table specific to a destination (the one for the pi-container to be dispatched) is updated, the process continues by notifying pi-nodes in the best-path (resulting from 'routing table') of the pi-container's dispatch (along with the essential information to assess the feasibility of reception) through a simple point-to-point communication. If some nodes of the optimal path decline the dispatch, the process proceeds with the second-optimal path and so on (in descending order of optimality). Once the next optimal pi-nodes have been designated by the actual pi-node P, the pi-container T is "informed" of the route and the same pi-container will publish this data in the following Pub/Sup Topic:

Topic Pub/Sub:

#/state/pi-container/<unique-identifier-pi-containerT>

Publishers: smart pi-container T with tracking, monitoring, and data-sharing capabilities

Subscribers: pi-shippers (and senders) interested in monitoring the shipment throughout the entire journey (on behalf of clients or providing tracking services to clients) pi-nodes interested in understanding the state of pi-containers flowing through their facility and all other pi-actors will come into contact with that pi-container.

Whenever a pi-container arrives at a pi-node the route assigned to it can be updated by trying to take advantage of routing opportunities that contingencies may offer or to avoid network turbulence that could delay arrival at the destination. The route assigned to a pi-container is updated in the same way explained above.

Pi-carrier assignment to a specific pi-container to ship

Once the next optimal pi-node P' has been designated, the current pi-node N is responsible for assigning the transport of the pi-container T between its node and the next one to a pi-carrier. For the pi-carrier assignment, once again, the pi-node N uses a Pub/Sub Topic in it publishes the transport request, providing all the details of the pi-container C.

Topic Pub/Sub:

#/auctions/pi-containers-transportations/Network A/ District 1

Publishers: pi-nodes publishing their request of transportation of pi-containers that need to be transmitted to the next pi-node. Therefore, also pi-node N will publish the transportation request as for pi-container C.

Subscribers: pi-carriers operating in network A and district 1 interested to take charge of new pi-containers to transport.

Once pi-nodes N publish delivery requests with related information (destination, time-related info, freight requirements), including the one of pi-container C, all pi-carriers must carefully assess the available requests from the pool to determine which delivery requests align best with their capabilities. After this choice, interested pi-carriers will submit their bids for pi-container C and the auctioneer (pi-node N) undertakes the winner decision process (WDP). The auctioneer then disseminates the results to the losing pi-carriers while providing detailed information to the winning pi-carrier R and the pi-shipper P involved, including payment details.

Composition/Decomposition of pi-containers assigned to a truck (pi-carriers)

Another crucial activity carried out by pi-nodes is the composition/decomposition of pi-containers. Once the pi-containers arrive at a node, they are eventually unloaded from the pi-truck/train and have to be reloaded onto another vehicle. In order to have an optimal and efficient utilization of pi-means and avoid excessive handovers the PI requires containers to be composed and decomposed among themselves (thanks to interlocking and gripping mechanisms) according to several factors.

Therefore, following the scenario described above, once the pi-carriers has been selected for specific bundle of pi-containers, the node has to decompose composed pi-containers just unloaded and recompose them for next transportation (assigned to the selected pi-carrier). In order to optimize this process, pi-node N can access necessary information at different topics Pub/Sub.

Topic Pub/Sub:

#/state/pi-container/<unique-identifier-pi-containerT>

Publishers: smart pi-containers with tracking, monitoring, and data-sharing capabilities publishing information about their state and the one of the shipping good encapsulated therein

Subscribers: pi-node interested to optimize the composition/decomposition activities and utilization of pi-means accessing data about pi-containers assigned to the specific pi-carrier.

The pi-node, through this channel Pub/Sub has the possibility to take composition/decomposition decisions according to same pi-containers' unloading destination, environmental requirements, pi-shipper managing the shipping request. Moreover, given an adequate computational infrastructure the pi-node can take pi-containers' future states into consideration (considering next node in the route or future disturbances and needs).

Topic Pub/Sub:

#/state/pi-truck/<unique-identifier-pi-containerT>

Publishers: truck's driver/owner and smart pi-trucks with tracking, monitoring, and data-sharing capabilities

Subscribers: pi-node interested to optimize the composition/decomposition activities and utilization of pi-means accessing data about pi-trucks assigned to bundles of pi-containers.

On the other hand, in order to have an efficient utilization of pi-means, it is crucial to access and elaborate data about trucks. With this purpose, the pi-node can access this information through the topic Pub/Sub illustrated above, optimizing the composition/decomposition of pi-containers and in turn the loading of pi-trucks. This optimization can be carried out according to available space on trucks/trailers (Frequently, trucks arrive at PI-nodes with a cargo of PI-containers. At these nodes, a portion of these containers is offloaded, while others remain onboard to be unloaded at subsequent nodes along the trucks' route) and specific spatial requirements to facilitate next unloading activities.

6. Conclusion and Discussion

The Physical Internet paradigm promises to revolutionize current logistics addressing the grand challenge characterized by the unsustainable and inefficient performance of the existing logistics operations. To accomplish this objective, PI leverages on the interconnectivity and interoperability among the fragmented logistics networks to facilitate resource sharing and optimization.

In this regard, the present thesis work has clarified the types of information and data exchanged in various logistical processes within the Physical Internet. This was achieved through a systematic literature review of PI protocols, which also enabled the establishment of a precise categorization of messages and data exchanged based on the identified core processes. The categorization served as an initial framework (offering a structured and organized approach) for conducting a critical analysis of the literature and accordingly examining how different categories of communication protocols were discussed in the publications (objects of analysis).

From the systematic literature analysis, it became evident that there was a gap concerning a shared, consolidated, and structured standard model that allows various actors within the Physical Internet to exchange information within the network, for example information about PI entities' states (such as pi-containers, pi-means, pi-nodes, pi-links, etc.), and to access specific and potentially elaborated information that the network possesses. This would help overcome the need for point-to-point communication (1 to 1 communication), especially for most logistics processes.

As a contribution to enabling the Physical Internet, this thesis has proposed a data exchange architecture capable of serving most of the logistics pi-processes by employing a Pub/Sub system (asynchronous and scalable messaging system), it was possible to provide a service that decouples the exchange of information and data in a context like the PI, which involves one-to-many or even many-to-many relationships. In fact, through the proposed data exchange system, this thesis has designed critical Pub/Sub topics to support the vital logistics processes for the Physical Internet, demonstrating their functionality through the development of illustrative use cases. Therefore, the resulting data exchange architecture appears to partially support the universal interconnectivity that the Physical Internet promises, enabling open data sharing and access.

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