Towards the Physical Internet – Logistics service modularity and design implications

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Abstract

The Physical Internet (PI) is a modularization of logistics services: standardized protocols, full interoperability and standardized packaging, PI-containers, and encapsulated freight. The PI-containers are a core component of the PI; however, previous PI studies have not addressed those containers' repositioning, despite its importance and effect on the PI network efficiency. In this paper, we analyze how the PI-containers' design and characteristics will determine the containers' flows in a domestic network context. The flows are studied strategically using a linear programming model minimizing flow imbalances between hubs and simulating the effect of PI-container compatibility. The model is tested using inter-regional freight data from Sweden, and the results are framed using modularity theory. Our analysis reveals that PI-container compatibility in terms of forward and reverse flows determines whether PI presents increased or decreased empty runs compared to the existing conventional logistics system. Departing from modularization theory, we discuss our results, emphasizing not only the importance of keeping synergistic specificity low but also how the characteristics will affect the urgency of technology use. Our implications are important to supply chain managers and policy makers for the future research on the Physical Internet, PI-container repositioning and routing, and packaging design.

Keywords: Physical Internet, Packaging logistics, Freight imbalances, Service modularization, Linear programming

INTRODUCTION

The economic; social; and perhaps most importantly, environmental challenges of today's supply chains call for new approaches to supply chain management (Montabon et al. 2016). The success of horizontal collaboration projects like CO3 (CO3 Project 2014) and industry-led collaboration projects (Creemers et al. 2017) have inspired the development of the Physical Internet (PI or π) (Mervis 2014; Montreuil 2011). PI is an innovative concept using the Digital Internet as a metaphor for shared resources such as transportation and warehousing, with freight encapsulated in PI-containers (Landschutzer et al. 2015; MODULUSHCA 2016) and transported through a standard protocol (Ballot et al. 2014; Montreuil et al. 2012). Compared to the conventional logistics system, PI represents a radically different system (Ambra et al. 2020; Ballot et al. 2014) that will force private and public stakeholders to re-think their supply chain strategies.

Major policy makers such as the European Commission have adopted the PI as the target vision for European logistics in 2050; worldwide, major industry stakeholders, associations, and authorities are joining the strategic initiative ALICE[1] in an effort to diffuse the Physical Internet (ALICE 2019; Ambra et al. 2019; Pan et al. 2017). Several studies have outlined tremendous potential improvements through both the PI concept and the adjacent area of sharing transportation and warehousing (Creemers et al. 2017; Pan et al. 2013). Ballot et al. (2012) reported a 20% reduction of fuel consumption; Sarraj et al. (2014a) noted a possible

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[1] ALICE is the acronym for Alliance for Logistics Innovation through Collaboration in Europe, a lobby organization formed to develop a strategy for research, innovation, and market deployment of European supply chain management innovation. Among the members are major corporations like Ford, Proctor & Gamble, Daimler, and Volvo; public stakeholders like National Italian Post and Port of Barcelona; and numerous research institutes like Mines ParisTech, Fraunhofer, and RISE (https://www.etp-logistics.eu/?page_id=29).

60% CO_2 reduction; and Yang et al. (2017) showed that logistics cost might in some cases be reduced by as much as 73%. Because the Physical Internet promises to improve economic, environmental, and social sustainability as well as attract significant public and private investment, its anticipated adoption and effects are highly relevant to practitioners, policy-makers, and scholars alike (ALICE 2019; Sternberg and Norrman 2017).

Terminal automation (i.e., automated loading and unloading) enables a new paradigm of supply chain network design as supply chain professionals today try to avoid the risks and waste associated with loading and unloading (Hübner and Ostermeier 2019). Today, the lack of standardized packaging, such as the PI-containers, is a barrier to terminal automation, hindering potential efficiency gains (Mervis 2014; Montreuil et al. 2015). According to Montreuil et al. (2015), "The Physical Internet strictly deals with goods encapsulated in standard modular π-containers that are to be the material-equivalent to [the Digital Internet's] data packets," (p.2). The PI-containers will be available in many variations and sizes and accommodating virtually all types of products (Montreuil et al. 2013) and load units. A supply chain's ability to efficiently reposition or back load returnable packaging such as a PI-container to a large extent depends on the characteristics of the returnable packaging. Packaging with specific characteristics that render it incompatible with loading of other types of goods will cause increased empty running (McKinnon and Ge 2006). Given that the PI-containers are different sizes and not centrally routed, Sternberg and Norrman (2017) emphasize the strategic importance of analyzing the multiple PI-containers' effect on freight balances because repositioning returnable packaging or any type of container is crucial to accurately estimating efficiency gains (Kolar et al. 2018; Kuzmicz and Pesch 2019; Mollenkopf et al. 2005).

Despite the potential of and significant research on PI (Ballot et al. 2016), Treiblmaier et al. (2016) notes that research on the Physical Internet has generally failed to incorporate theory and that the theoretical base is "highly underdeveloped" (p. 15). To the best of our knowledge, the detailed protocols, packages (PI-containers), and interfaces defined in the PI's blue-prints (cf., Ballot et al. 2014; Meller et al. 2013) make it the most extensively specified service modularization (Starr 2010) known to the field of Supply Chain Management.

This paper's purpose is to analyze PI-containers from a strategic logistics perspective (Bartolacci et al. 2012). We draw on theory of service modularity to frame antecedents to the Physical Internet's future effects, responding to several quests for research on the Physical Internet (Ambra et al. 2019; Pan et al. 2017; Sternberg and Norrman 2017; Treiblmaier et al. 2020). Given that the Physical Internet's goal is to meet the grand sustainability challenge of logistics (Montreuil 2011), the effect of PI-container repositioning determines future benefits, a crucial factor determining intention to strategically adopt new innovation (Premkumar et al. 1997; Venkatesh et al. 2003). Thus, as a starting point to investigate the effects of PI-containers' characteristics, we pose the following research question: *What are the implications of Physical Internet service modularity on PI-container flows?* In other words, how does the level of service modularity (or PI-container compatibility in regional transport) affect the PI-container flows and, more specifically, PI-containers' repositioning?

We contribute to the ongoing discussions with insights for both policy-makers and supply chain researchers in the areas of Physical Internet strategy and contextualized mid-range theory (Stank et al. 2017) of logistics service modularization (Voss et al. 2016). Furthermore, we extend the traditional maritime container repositioning literature by elaborating on the specifics of the PI-containers. Because the Physical Internet does not yet exist, this research is conceptual, however, we use empirical data in a linear programming model to analyze the expected effects, a methodological approach commonly used for maritime container repositioning (Kuzmicz and Pesch 2019; Shintani et al. 2007). The General Modular Systems' theory by Schilling (2000) is used for framing the results.

This paper's focus is modularity and packaging logistics (input into the modular system) in intra-regional transportation of general cargo, i.e., terminal-to-terminal transportation. Thus, first- and last-mile problems are outside this paper's scope. As will be discussed we examine strategic logistics effects in a hybrid system (Fazili et al. 2017), focusing on the strategic level of demand, supply, and transportation. As only approximately 1% of general cargo in Sweden is transported by railway (Sandberg et al. 2016), our analysis focuses on road transport of general cargo. Our results highlight the importance of maintained service modularity in the transport system, showing that the Physical Internet joint loading represents an efficiency improvement, offsetting the additional packaging material to be transported. However, our results also highlight that if service modularity is reduced through a lack of compatibility of transport packaging, the efficiency gains fail to materialize. This is of major importance to future SCM strategy and policy-making, as it emphasizes conditions where Physical Internet is part of tackling the grand challenge.

RELATED LITERATURE

This section outlines some of the concepts related to PI: packaging logistics and fill rates, the PI's components, and modeling of maritime container repositioning. For a more extensive or general discussion of the concept, see Ballot et al.'s (2014) book on PI or Treiblmaier et al.'s (2020) recent literature review.

Packaging logistics and fill rates

Packaging usually refers to different levels of packaging in the logistics system. *Primary packaging* is closest to the product and is often the consumer or sales packaging. *Secondary packaging* contains a certain number of primary packages, often termed *retail packaging*. *Tertiary packaging* contains several secondary packaging items, often referred to as *transport* *packaging*, such as a Euro-pallet. *Packaging logistics* focuses on the synergies achieved by integrating the packaging systems and logistics (Pålsson and Hellström 2016).

Balanced transport flows are one of the keys to high fill rates and sustainable freight transportation, yet freight imbalances characterize logistics in most parts of the world (Hesse and Rodrigue 2004). Imbalanced flows and deadheading are even more common in certain parts of the distribution process, such as first- and last-mile logistics. Over longer distances, balancing flows becomes more important. For example, in Scandinavia, the northbound and southbound flows in Norway, Sweden and Finland differ largely both in terms of volume and types of goods transported (Vierth et al. 2012; Wall 2013). Hence, being able to transport different types of goods depending on the direction of inter-regional flows is crucial. McKinnon and Ge (2006) analyzed potential backhauling in the UK and found that the incompatibility of vehicles and products (i.e., the packaging) was one of the major factors behind empty running.

Components of the Physical Internet

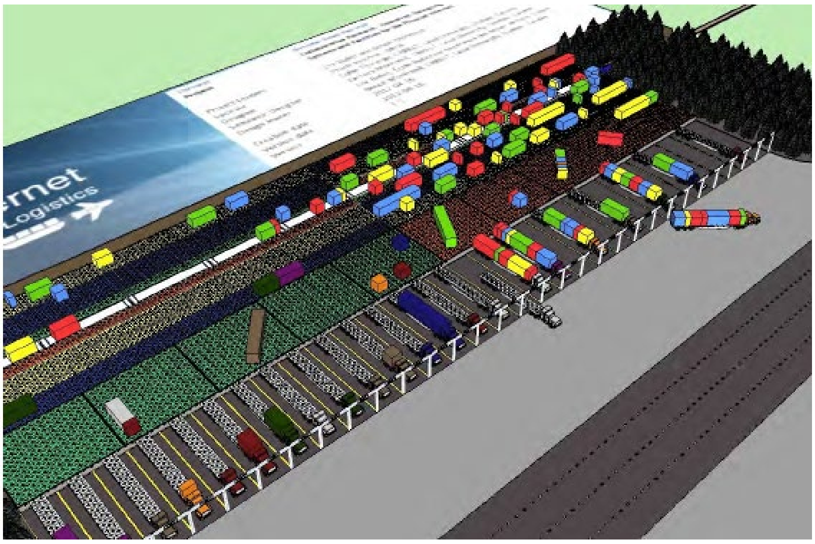
According to researchers such as Ambra et al. (2019) and Matusiewicz (2020), the Physical Internet, the vision for logistics by 2050, contains a detailed roadmap of the concept's development and significant milestones through ALICE (2019). In this section, we elaborate on the PI-infrastructure and the PI-containers.

PI-infrastructure

Ambra et al. (2019) describe the Physical Internet's mechanics as follows: "The PI is inspired by the metaphor of the Digital Internet which uses packet switching; the message is split into different pieces (packets) that travel over the internet via various routes and are then brought together at the receiver's side. The packets are routed through an interconnected network of nodes/hubs (PI-hubs) depending on the network capacity. This dismantling approach is thus being adapted by the PI where the physical goods or, in more general, physical objects can be routed via different links from their origins to destinations in standardised containers using standardised handling procedures" (p. 1607).

Several PI papers have addressed protocols (Montreuil et al. 2012; Sarraj et al. 2014a) and routing (Ballot et al. 2012; Sarraj et al. 2014b). As all hubs will be interoperable, a distinct advantage of the Physical Internet would be that virtually all lanes could be trafficked by full trucks, a big reason for the concept's previously outlined improvements relative to conventional systems. PI-hubs are designed to automatically handle inbound and outbound PI-containers (See Figure 1) (Ballot et al. 2013).

Figure 1. PI-hub for intermodal transportation (Ballot et al. 2013). (The authors will request permission to reproduce the image. Figures and tables are temporarily included in the manuscript for readability purposes).



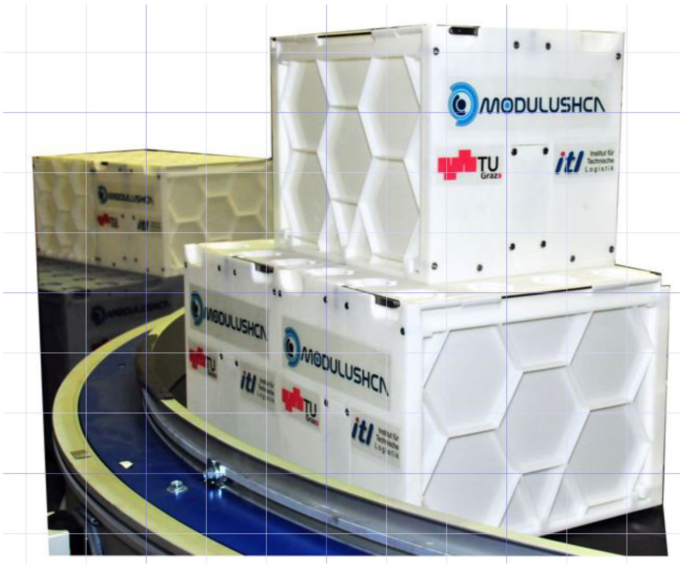
Due to their anticipated fast and autonomous handling, time windows lose their relative importance (cf. how the Digital Internet ships data packages) because constraints in terminal-to-terminal transportation only become a major concern when goods are going from a terminal to a consignee.

PI-containers

The PI-container system is an integral part of the Physical Internet (Ballot et al. 2014; Montreuil 2011). All goods are packed in PI-containers, which are stackable and can be handled in automated PI-hubs (Montreuil et al. 2013). Sallez et al. (2016) describes the three main categories of PI-containers. The *packaging containers*, those closest to the product, are the primary packaging. *Handling containers* hold an individual product, a cluster of products, or several packaging containers (secondary packaging). Finally, *transport containers* hold the handling containers for transportation (tertiary packaging). PI-containers are assumed to replace the pallets on which different types of freight can be loaded. Russian dolls are often used to illustrate the nesting of the PI-containers (Montreuil 2011).

Landschutzer et al.'s (2015) paper and the final report of the European Commission project MODULUSHCA's (2016) describe two cases of PI-containers: the handling container named *m-box* (see Figure 2) and the transport container referred to as the *unit load PI-container*. The m-boxes are loaded into the unit load PI-container, and the unit load PI-containers are loaded onto an EU-trailer (Landschutzer et al. 2015). The MODULUSHCA project's m-box fits standard European trailers (EU-wide standard max length 16.5m, maximum weight (truck + trailer) 40 tons). However, if used with TEUs, the use of the boxes would create a lot of ullage (due to the inherit incompatibility of EU-pallets and TEUs), an issue that remains unresolved.

Figure 2: An m-box (MODULUSHCA 2016), 400 x 600 x 400mm. (The authors will request permission to reproduce the image. Figures and tables are temporarily included in the manuscript for readability purposes.)



Although the m-boxes are currently not foldable, the folding function is expected in the next generation (MODULUSHCA 2016). Foldable PI-containers are compatible, as the folded PI-containers can be repositioned with any category of goods.

The literature suggests additional possible dimensions of PI-containers, which are assumed to be stackable, enabling high fill rates of the unit load PI-containers. Sarraj et al. (2014a) propose a set of modular PI-containers with different sizes (2.4m*2.4m*[1.2, 2.4, 3.6, 4.8, 6, 12] m). This modularity is based on the "pallet-wide" (PW) container, which is an intermodal transport unit used in Europe. According to Sarraj et al. (2014a), these sizes represent potential sizes. Using these sizes, they provide a Bin Packing Problem (BPP) formulation to pack the PI-containers by transportation modes (e.g., trucks) (Sarraj et al. 2014a). To study disruption problems at PI-hubs, Yang et al. (2017) used the same PI-container sizes and PI-container packing protocols (specifying how to assign freight to a best fit PI-container). Hauder et al. (2018) also suggest using the BPP problem to assign PI-containers to PI-movers (transportation modes).

Container repositioning

Flow imbalances between different regions in the network and the resulting need for balancing flows of PI-containers are expected as in any system. In the PI, containers are expected to be commonly used by all shipping firms. Hence, PI-container repositioning is in theory easier, yet necessary due to incompatible freight types and trade imbalances among the geographical areas where the PI hubs are located. Kolar et al.'s (2018) recent study, based on a case study in the landlocked country of the Czech Republic, suggests that in practice, empty container repositioning is perceived as more of a global trade imbalance problem than as a problem of integrated resource or equipment allocation and vehicle routing. Due to this perception, ocean carriers primarily focus on solutions at a global rather than a regional level. In the literature, different aspects of the empty container repositioning problem have been addressed using mathematical modeling, linear, or stochastic programming (for example Jula et al. 2006; Song 2007; Yun et al. 2001). Kuzmicz and Pesch (2019) provide a detailed review of the optimization approaches for the problem terms of TEU and FEU container repositioning.

Linear programming, which is one of the commonly used approaches (Kuzmicz and Pesch 2019), assumes deterministic demands and provides minimum cost solutions for repositioning under different policies of container reuse. In the context of PI, empty container repositioning may also present a problem in terms of the PI-containers. Although PI-containers are assumed to come in different sizes, incompatible freight types and trade imbalances may still necessitate the need for empty PI-container repositioning. Considering the compatibility of PI-containers in their ability to hold (or be transported together with) different freight types, we study how much empty PI-container repositioning would be required under different compatibility scenarios. As articulated in Rogers et al. (2012), linear programming is suitable for scenario analysis by changing the parameters of interest.

THEORETICAL FRAME: MODULARITY IN LOGISTICS SERVICES

Modularity is considered a way to increase commonality across different versions or product variants within a system or a product family, i.e., to allow for the same component(s) to be used in several product variants (Salvador et al. 2002; Schilling 2000). A system can be defined not only at the industry or the organization level but also at the level of a product (goods or service) to be provided to the customer (Schilling 2000). Tuunanen et al. (2012) define a *service module* as "a system of components that offers a well-defined functionality via a precisely described interface and with which a modular service is composed, tailored, customized, and personalized" (p.102).

Interfaces are the mechanisms integrating the subsystems into a whole. In this respect, the interfaces ensure loose coupling, which allows the subsystems to function independently and permits substitution of subsystems as needed to alter the system itself. Salvador et al. (2002) explains, "As such, one motivation underlying the operations management research stream has been to understand the benefits of component commonality on operational performance, as well as the various factors that might affect these benefits" (p. 551).

Schilling (2000) has outlined a model for describing the factors driving integration (decreasing modularity) and disaggregation (increasing modularity): "At its most abstract level, it (modularity) refers simply to the degree to which a system's components can be separated (separability) and recombined" (p. 315). Schilling's modularity framework contains the following components:

- *Heterogeneity of inputs* refers to how easy or difficult the system is to modularize. The inputs into a service system include both the technological options available to achieve particular functions and the resources and capabilities of the firms involved in producing the service. For example, the characteristics of hot food bulk oil and frozen fish are very different. These heterogeneous inputs require specialized transport equipment (food tanker and freezer trailer, respectively), making them difficult to modularize. However, in the scenario of hot food bulk oil and frozen fish, if a modular system would be capable of handling these heterogeneous inputs in the same system, such a system could materialize significant transport efficiency gains.

- *Heterogeneity of demands* refers to the level of differences among the customers' demands. The more similar customer demands are, the more the system is inclined to increase modularization.
- The *synergistic specificity* of the system creates pressure against the system migrating toward modularity. Heterogeneous inputs in combination with heterogeneous demands will reinforce each other's effect, creating synergistic specificity toward less modularity.
- *Urgency* refers to technological change (or the speed thereof) and competitive intensity. Manufacturers with lucrative after-market sales will try to maintain the status quo and work against modularization. On the other hand, authorities such as the European Commission will try to enforce modularity through open interfaces and standards (e.g., European Commission 2016).

Schilling (2000) also argues that systems in general are characterized by inertia and that they do not respond immediately and vigorously. Revisiting over 45 years of modularity in the field of operations management, Starr (2010) explains that modularization in the manufacturing industry had not reached the anticipated adoption because low-cost manufacturing overseas represented a relatively larger savings for the industry. However, modularization in the context of transportation services, usually does not require engineering changes in products although exceptions exist and can be highly beneficial (Hellström and Nilsson 2011). While these changes may become very costly, they alter the means by which products are handled and transported. The Physical Internet's PI-containers and PI hubs may provide these means.

Schilling (2000) defines the primary action of increasing modularity as being able to combine and recombine heterogeneous inputs into a variety of heterogeneous configurations and suggests that "…, heterogeneity in the range of inputs, combined with heterogeneity in customers, creates powerful incentives to adopt a modular system" (p. 317). In the context of a logistics systems, due to the heterogeneity of inputs (goods), different packages or containers are used. These goods-specific packages can be considered components of a modular system that can be separated and recombined. For instance, a container's contents (packages or PI-containers) delivered to a hub can be separated and shipped out of the hub to another hub or to their final destinations. In contrast to product modularity, service modularity generally does not risk losing any transportation functionality because it is commoditized and because most receivers of goods have homogenous demands.

On the other hand, synergistic specificity, as a factor expected to decrease modularity, may be a hindrance when packages with the same origin and destination tag cannot be effectively combined in the same load unit. For example, assume a PI-container, such as an oil drum, is created to encapsulate one type of good. These PI-containers for drums must be returned to a production site after the oil has been consumed at the location of the demand. If the location produces goods packaged in PI-containers (such as m-boxes) that cannot be folded, the supply chain faces a double goods flow because the respective repositioning of each type of PI-container would be incompatible with the regular flow, i.e., generating a freight imbalance because the repositioning of the PI-containers is not separable. Hence, if the PI-container flows have a low level of compatibility, the Physical Internet is unlikely to be the strategy choice of shippers, who would not want to pay surplus charge for repositioning the empty PI-containers (i.e., the low level of compatibility represents synergistic specificity).

According to Schilling's (2000) framework, urgency is the last factor affecting adoption of modularity. In logistics, urgency stems from environmental and social sustainability demands pressuring haulers to change their ways. Urgency is also enabled and motivated by technological changes like cloud computing and the Internet of Things. It is noteworthy that modularity in the Physical Internet is paradoxical because the PI-containers, though clearly exemplifying modularization, also risk amplifying the inputs' heterogeneity. With the inputs' increased heterogeneity (causing incompatible flows of PI-containers), service modularity can be negatively affected. In this manuscript, we investigate these factors' effect on the Physical Internet's PI-container flows. We assume that heterogeneity in terms of both inputs and outputs (customer demand) remain constant in logistics industry. Therefore, we focus on synergistic specificity in terms of PI-container compatibility and on urgency in terms of technology use and environmental sustainability.

RESEARCH DESIGN

In the backdrop of service modularization and packaging logistics, our study uses mathematical modelling to address the strategic logistics' effects of the Physical Internet's PI-container flows. With extensive work done on some aspects of the concept but very little on PI-containers (Sternberg and Norrman 2017; Treiblmaier et al. 2020) as well as previous research on maritime container repositioning, PI's current state suggests that elaborating on the effects of the PI-container system's repositioning using mathematical modelling is suitable (Kuzmicz and Pesch 2019; Rogers et al. 2012; Shintani et al. 2007).

This paper offers a strategic analysis of the total volumes and balances of freight and PI-containers in a terminal-to-terminal network. The results are intended to offer strategic implications regarding PI adoption's effects on supply chain managers and policy makers. Hence, our deterministic model does not examine operations, seasonality, and other temporal factors, but rather focuses on the more important (from an adoption perspective) question of the overall effect of the PI-container's characteristics. As outlined by Waller and Fawcett (2012), a challenge in applying mathematical modeling to generate theory in supply chain and logistics has often been that the implications and assumptions have rendered the models less useful or impractical. To overcome this challenge, we have consulted various experts and practitioners in the logistics industry and have carefully observed the study's flows that are being modeled. The results from our consultations form the assumptions of this research. However, before describing the model and assumptions, we will discuss the dataset, SAMGODS.

Data and rationale– SAMGODS

To analyze PI's potential effects through the derived demand for distribution, we used Sweden as a quantitative case. Because the neighboring countries have similar freight flows and respective differences in north-south bound transportation, including data from those countries would not yield different results in terms of the relative effects of the PI-containers' compatibility level. All national volumes loaded and unloaded in Sweden were obtained by using the SAMGODS data (Bergquist et al. 2016; Karlsson and Bernhardsson 2018; Vierth et al. 2012), by courtesty of the Swedish Traffic Administration. It is an origin-destination matrix of all domestic freight flows in Sweden, with a municipality as the origin-destination. The data from the SAMGODS data has been used in numerous studies over the past decade (e.g., Jensen et al. 2019; Ljungberg 2013; Pålsson and Sternberg 2018; Pålsson et al. 2017), and Karlsson and Bernhardsson (2018) have explained its calibration. Located in the corner of Europe, Sweden provides access to high-quality freight data, has long freight distances, and has received much research attention; thus, Sweden is well suited for PI analysis.

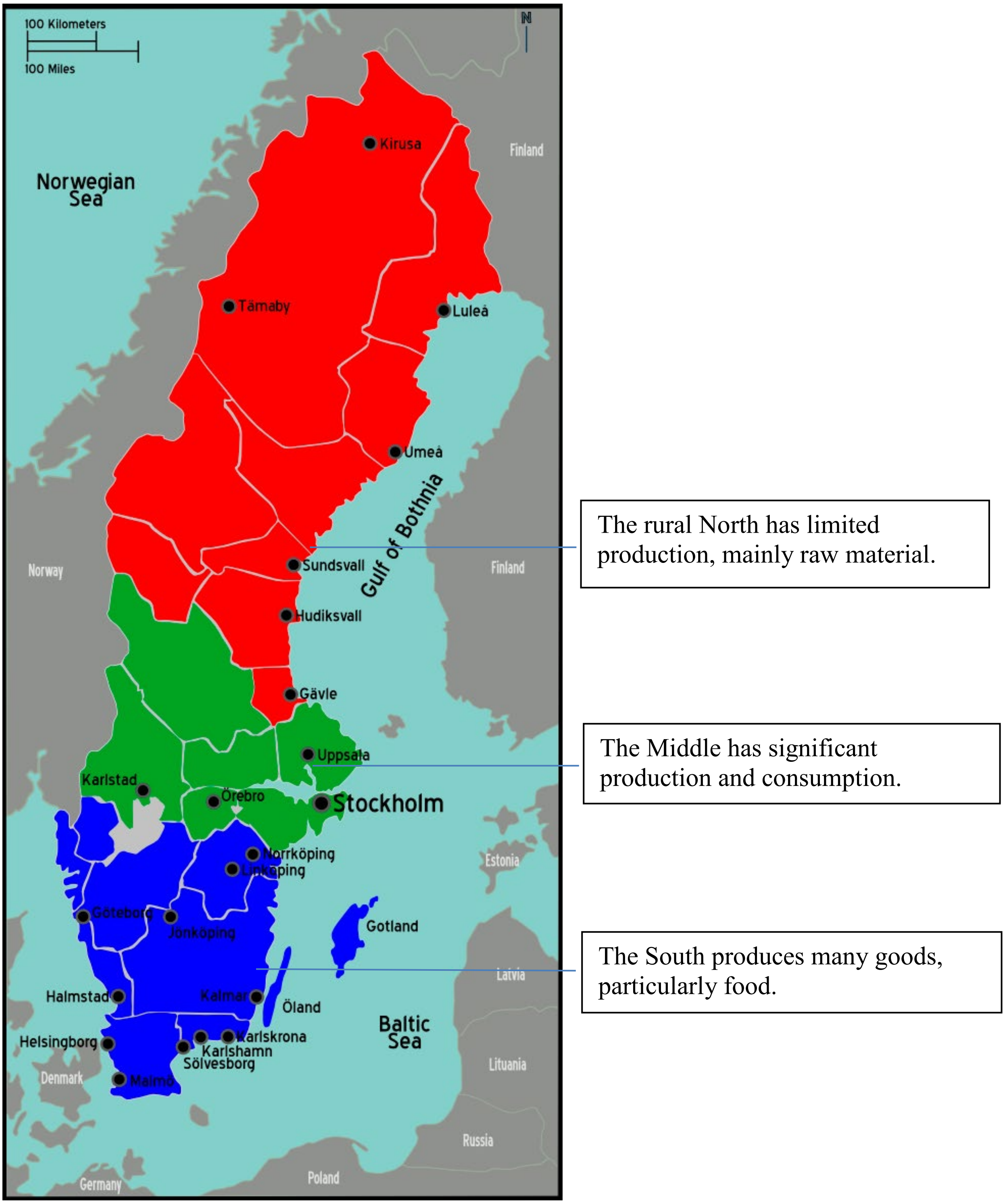
The SAMGODS data divides freight into 35 categories, based on their characteristics (e.g., palletized, tank, dry bulk, etc.) and type of vehicle required (e.g., freeze trailer, timber vehicle, etc.). To calculate the Physical Internet's effects on freight balances in Sweden, we focused on the 12 categories of freight in the SAMGODS data that are transported in the same vehicle combinations as the general cargo.

Table 1. The types of goods according to the SAMGODS data (Bergquist et al. 2016).

Commodity (type)	**Included in this study**
1 Cereals (Dry bulk)	
2 Potatoes, other vegetables, fresh or frozen, fresh fruit (Dry bulk)	X
3 Live animals (Dry bulk)	
4 Sugar beet (Dry bulk)	
5 Timber for paper industry (pulpwood) (Dry bulk)	
6 Wood roughly squared or sawn lengthwise, sliced or peeled (Dry bulk)	X
7 Wood chips and wood waste (Dry bulk)	
8 Other wood or cork (Dry bulk)	*No PWC matrix*
9 Textiles, textile articles and manmade fibres, other raw animal and vegetable materials (General cargo)	X
10 Foodstuff and animal fodder (General cargo)	X
11 Oil seeds and oleaginous fruits and fats (Liquid bulk)	
12 Solid mineral fuels (Liquid bulk)	
13 Crude petroleum (Liquid bulk)	
14 Petroleum products (Liquid bulk)	
15 Iron ore, iron and steel waste and blast-furnace dust (Dry bulk)	
16 Non-ferrous ores and waste (Dry bulk)	
17 Metal products (General cargo)	X
18 Cement, lime, manufactured building materials (Dry bulk)	
19 Earth, sand and gravel (Dry bulk)	
20 Other crude and manufactured minerals (Dry bulk)	
21 Natural and chemical fertilizers (Dry bulk)	
22 Coal chemicals (Liquid bulk)	
23 Chemicals other than coal chemicals and tar (Dry bulk)	X
24 Paper pulp and wastepaper (Dry bulk)	
25 Transport equipment, whether or not assembled, and parts thereof (General cargo)	X
26 Manufactures of metal (General cargo)	X
27 Glass, glassware, ceramic products (General cargo)	X
28 Paper, paperboard; not manufactured (Dry bulk)	
29 Leather textile, clothing, other manufactured articles than paper, paperboard and manufactures thereof (General cargo)	X
30 Mixed and partial loads, miscellaneous articles (General cargo)	*No PWC matrix*
31 Timber for sawmill (Dry bulk)	
32 Machinery, apparatus, engines, whether or not assembled, and parts thereof (General cargo)	X
33 Paper, paperboard and manufactures thereof (General cargo)	X
34 Wrapping material, used (Dry bulk)	*No PWC matrix*
35 Air freight (General cargo)	

The 12 categories were selected in collaboration with industry experts and after visual inspections of North-South and South-North bound flows. We used Sweden’s three geographical regions as a representation of intra-regional freight flows (See Figure 3). These regions represent significant diversity in terms of supply and demand of goods. Figure 3 provides a simplified overview of Sweden’s regional supply and demand for goods.

Figure 3. The three regions of Sweden: South (blue), Middle (green) and North (red). Higher-resolution image available at https://sv.wikivoyage.org/wiki/Sverige#/media/File:Map-Sweden01.png.



In terms of modularity, the compatibility between different transports of PI-containers determines whether the Physical Internet will decrease modularity (as described in the previous section). Future Physical Internet implementations might include PI-containers adopted for bulk goods, meaning that PI could possibly increase modularity. However, such implementations are more likely to appear after a critical mass of PI-hubs and participating operators have been realized.

Experts' contributions to assumptions

The quality of any model depends on underlying assumptions (Waller and Fawcett 2012), thus we consulted with six physical distribution experts between 2012 and 2018 (Table 2). These experts were selected based on their competence and experience in real-world logistics, with a specific focus on terminal-to-terminal operations in nation-wide Swedish operations.

Table 2. The six experts providing input about the assumptions. The last column refers to specific contributions to the "Assumptions" section.

Expert #	Data	Takeaways and Special Notes	Contribution to Assumptions
1. Senior macro transport consultant	Two interviews and several emails 2016-2017	The senior macro consultant aided the researchers in proposing compatible freight types as well as making correct aggregations of SAMGODS data. The consultant reviewed an earlier version of this paper.	#3 & 6
2. District manager (international logistics service provider)	Phone interview 2012	The district manager explained the horizontal and vertical collaboration between the logistics service providers and customers in rural North Sweden.	#2
3. CEO and 4. Head of Member Relations (hauler association)	Several physical and phone meetings 2016-2018	The hauler association represents over 100 road haulage companies operating line haul and distribution for a major logistics service provider. The CEO and the head of Member Relations provided valuable input on how their member companies operate their lines in the logistics service provider's hub-and-spoke system.	#2, 3 & 7

5. Operations manager of road hauler operating a terminal	Two phone interviews and several emails 2017	The operations manager of this road hauler in North Sweden manages a hub and oversees loading of south-bound and unloading of north-bound goods. For over two weeks, the operations manager took systematic photos of the loading of all incoming and outgoing trucks.	#2, 3 & 6
6. Driver (major national logistics service provider)	Several informal discussions 2017	A driver employed by a major national logistics service provider took, with permission, pictures of all outbound trucks from the Gothenburg terminal. This driver has over 20 years of experience with all types of vehicles and has been involved in numerous research and development projects about driver efficiency. He was informed of the Physical Internet; helped as a discussion partner; and provided input on fill rates, packaging, and weight assumptions.	#3

Traditionally, mathematical models are validated by real-world data. Because no real-world Physical Internet exists, there is no real-world data to validate the model, increasing the importance of using trusted input data and appropriate assumptions when analysing the Physical Internet.

THE MODEL

Based on our research question and SAMGODS data, we formulated a mathematical model mimicking the Physical Internet. The model has the objective of minimizing the imbalances in PI-container flows between PI-hubs. As discussed earlier, flow imbalances can be due to trade imbalances among the regions or different types of freight needing different PI-container types. We assume that the amount (in tons) and the types of freight that a hub should supply to other hubs indicate its demand for the amount (in tons) and types of PI-containers. Similarly, the amount (in tons) and the types of freight that a hub should receive from other hubs indicate its supply for the amount (in tons) and the types of PI-containers. Once the characteristics (size and weight) of the PI-container used for a specific freight category is known, the number of PI-containers of that type (based on size) can be calculated for the amount to be carried in that type/size of PI-container. Based on the PI's premises, we assume that the PI-containers are routed automatically via different routes from their origins to destinations (our focus being terminal-to-terminal transportation). The objective is to move PI-containers between terminals while minimizing the reverse flows, i.e., empty PI-container repositioning. Our model is applicable to inter-regional transportation in a Physical Internet and is not dependent on whether the first- and last-mile to the respective regional PI-hub are travelled in the PI or through conventional transportation (Fazili et al. 2017).

The model is general enough to handle any number of nodes in the interconnected network of PI-hubs and any number of freight types. One important aspect that we want to analyze is the compatibility of the flow of PI-containers with the actual freight. For this purpose, our model handles four *compatibility scenarios* as detailed below, where K indicates the number of types of freight and C indicates the number of PI-container compatible groups.

- With full compatibility, which is the best case, all freight types can be combined so that there is only one ($C=1$) type of PI-container that has to be counted for.
- With no compatibility, which is the worst case, each freight type must be carried separately in $C=K$ different types of PI-containers.
- With limited compatibility, which is closer to the no-compatibility case, freight must be carried in $C=2K/3$ different types of PI-containers.
- With some compatibility, closer to the total-compatibility case, freight must be carried in $C=K/3$ different types of PI=containers.

We provide models for each of the four cases explained above. The models remain the same except for the value of C (the number of compatibility groups) and the freight types in each compatibility group. After the main hub in a region is reached, the flows within that region are outside our model's strategic scope. First, we define the notations used in the flow balancing model:

Sets

$H = \{1,...,N\}$; set of all hubs

$F = \{1,...,K\}$, set of all freight types

$F^p \subset F$ = subset p of freight types that are compatible in terms of PI-containers

$p=1,..,C$

Indices

$i, j \in H$ indicates regional hubs

$k \in F$ indicates freight or PI-container type

$p=1,..,C$ indicates a group of compatible freight types

Parameters

D_{jkp} : Demand in tons for PI-containers in hub j for freight type $k \in F^p$ for $p=1,..,C$

S_{ikp} : Supply in tons for PI-containers in hub i for freight type $k \in F^p$ for $p=1,..,C$

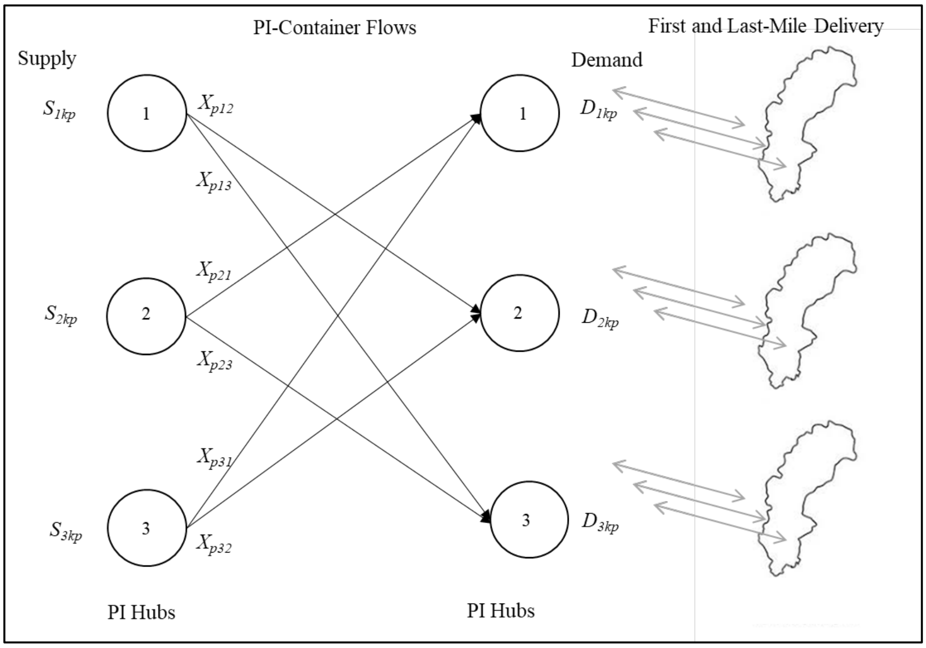
Decision Variables

X_{pij} : the flow in tons of freight from hub i to j for $p=1,...,C$ (total for all $k \in F^p$)

fb_{pij} : the difference in tons between the flows between hub i to j and hub j to i for $p = 1,...,C$ (total for all $k \in F^p$)

Figure 4 depicts the network Model PI^C model.

Figure 4. Network representation of the flow balancing model.



In Model PI^C, $C \in \{1,4,8,12\}$ indicates the assumed compatibility. In this sense, we have four equivalent models.

Model PI^C

$$Min \sum_{p=1}^{C} \sum_{i=1}^{N} \sum_{j=i+1}^{N} \left| fb_{pij} \right| \tag{1}$$

Subject to

$$\sum_{j=1}^{N} X_{pij} \leq \sum_{k \in F^p} S_{ikp} \quad for\ all\ i\ and\ p \in \{1, \dots, \mathrm{C}\} \tag{2}$$

$$\sum_{i=1}^{N} X_{pij} = \sum_{k \in F^p} D_{jkp} \quad for\ all\ j\ and\ p \in \{1, \dots, C\} \tag{3}$$

$$fb_{pij} = X_{pij} - X_{pji} \quad for\ all\ p\ \in \{1, \dots, C\}, i \in \mathrm{H}, and\ j = i+1, \dots, N \tag{4}$$

$$X_{kij} \geq 0 \quad for\ all\ k \in F^C\ and\ i,j \in H \tag{5}$$

$$fb_{kij}\ unrestricted\ \ k \in F^C\ and\ i,j \in H \tag{6}$$

In the objective function (1) of Model PI^C, we calculate the total flow imbalances between the origin and destination hubs. It should be noted that the function includes an absolute value function making the model nonlinear. We later linearize this function by adding new variables and constraints to the model (Appendix A). In constraint set (2), we ensure that the PI-containers going from hub j to the other hubs do not exceed the number received in hub j (see Figure 4). In constraint set (3), we ensure that hub i receives all the PI-containers it needs (see Figure 4). In constraint sets (2) and (3), we consider each compatibility group, p, as one aggregate commodity and, therefore, calculate the total supply and total demand for group p by summing over the supply and demand of the commodities in that group. The maximum value of p comes from C, indicating how many compatibility groups are in each scenario. In constraint set (4), we calculate the flow imbalances for each compatibility group p between each hub.

The PI-containers must be repositioned; thus, we must only calculate the imbalances in one direction because they will be same in the reverse direction. Constraint set (5) ensures the non-negativity of flows, and constraint set (6) specifies that imbalances are unrestricted in sign.

In order to solve the model as a linear program, the objective function must be linearized by adding a new set of variables and constraints to the models, as detailed in Appendix A.

Assumptions

This section discusses our paper's underlying assumptions.

Assumption #1: Hybrid logistics network

Given the huge investments and the time necessary to build the Physical Internet's components, decades of hybrid systems are in the future. Fazili et al. (2017) describe a hybrid system, i.e., the conventional logistics system co-existing with the Physical Internet. Hence, the assumption of a hybrid system is the most realistic and the one applied in this paper. The implementation of such a hybrid logistics network assumes that the border between the conventional and the PI logistics systems can be the PI-hub, i.e., goods can be unloaded into the PI-hub and packaged in the hub's PI-containers. Given its strategic context (Bartolacci et al. 2012), this manuscript describes the system's "PI" (intra-regional terminal-to-terminal transportation).

Assumption #2: Truck fill rate on imbalanced lanes

With its long distances, rural towns and villages, Northern Sweden is characterized by significant horizontal collaboration (described by, for example, Hagebäck and Segerstedt (2004)). The two largest food retailers, ICA and COOP, jointly distribute to food retailers; and logistics service providers Schenker and DHL collaborate. This collaboration is driven by the absolute necessity to maximize fill rates, as verified in an interview with a Northern district manager (Expert 2). Though not as strongly enforced, lanes to areas with high demand for goods (e.g., Stockholm) are virtually full. Thus, the motor carriers know they are highly unlikely to get a backhaul and will have to return empty (Experts 3, 4, and 5).

Assumption #3: Packaging weight and foldability

General cargo is generally not palletized goods, but rather construction material and components, drums, barrels, vehicle components, etc. that all represent the freight flows between origin and destination – usually with different types of freight going in the respective directions (Experts 1 and 5 and freight dataset).

We assume, for the sake of our model, that the packaging weight (and capacity) of the medium m-box (400x600x400) represents all types of either smaller or larger PI-containers (or m-boxes and future specialized versions of m-boxes). This assumption will not be true, as specific PI-containers designed for one or more types of goods will have different size than the m-box, however it will not to any great extent effect the results (which is looking at the aggregated network effect). According to Landschützer et al. (2018), a regular m-box weighs 4.5kg. The m-box is designed in relation to the Euro-pallet (800mm x 1200mm base), i.e., 4 m-boxes can be loaded per pallet (base) and stacked 6 tall. Given that a regular Swedish combination is 18 (truck) + 33 (trailer) pallets, the packaging weight is 51 x 4 x 6 x 4.5kg = 5508kg (1224 PI-containers (m-boxes) * 4.5kg). In transporting general cargo in Sweden, the vehicle combination's volume constraint is typically the limiting factor rather than the weight limit[2]. A full truck is 25 tonnes and can fit 1224 m-boxes. Hence a representative PI-container is assumed to carry 20.42kg. Although the m-boxes are not currently foldable, we assume they will be in future versions (in the scenarios of compatible flows); otherwise, the entire Physical Internet becomes a one-lane system with PI-containers full going out and empty going back (synergy specificity as explained in the frame based on service modularity).

Assumption #4: Aggregate imbalances

To the best of our knowledge, the flow imbalances between the origin and destinations have not been addressed in the PI context (Sternberg and Norrman 2017). In contrast, our model addresses this issue at an aggregate level. We do not include any operational constraints (e.g., time windows, lead times, loading-unloading), which are critical for operational level planning in PI; however, they are unnecessary for determining the imbalances' effects. Our purpose is not to provide a detailed solution to an operational PI problem (c.f. Hauder et al. 2018), but to study how trade imbalances and freight (in)compatibility may generate a need for empty PI-container repositioning.

Assumption #5: Economy of product diversity

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[2] This is according to Experts 3, 4, 5 and 6, as well as in numerous studies of average weights (Wall 2013). The exception (when the weight is the constraint rather than the volume) is generally raw materials (Pålsson and Sternberg 2018).

An underlying assumption is that the heterogeneity of demands of logistics and transport services will remain constant, i.e., customers will continue consuming a large variety of goods, i.e., economy of product diversity (Suzuki and Lu 2017). Given these considerations, the fill rates supplied by Wall (2013) and Pålsson and Sternberg (2018) as well as the PI-containers' weight, we have used 25 tons as the weight when a truck combination's maximum volume capacity is utilized (as previously explained, the volume rather than the weight determines when a truck transporting general cargo is full).

Assumption #6: Compatibility of PI-containers (freight categories)

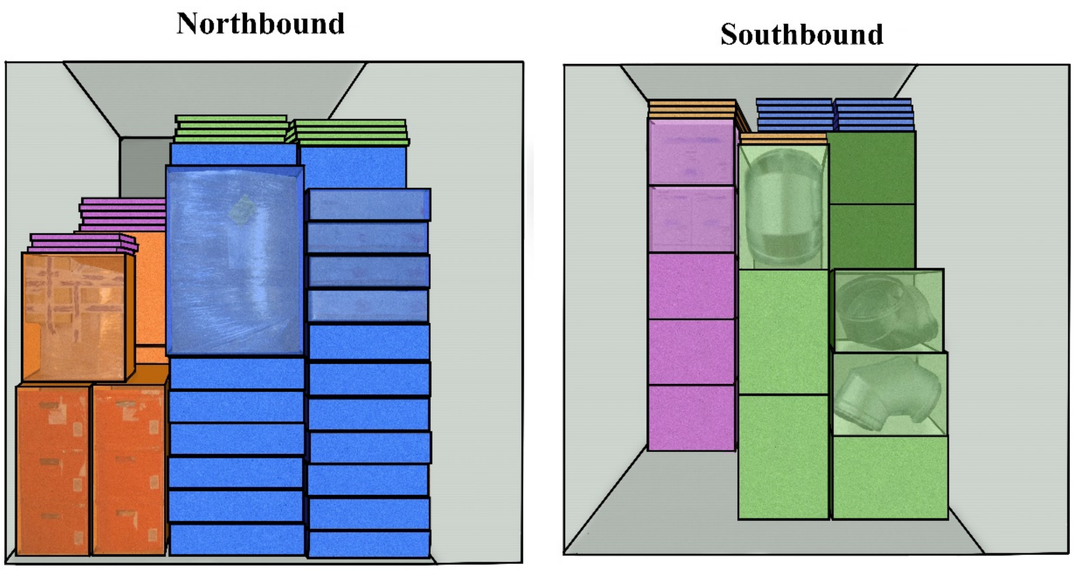
The 12 identified freight categories (SAMGODS) are currently transported using the same truck and no designated transport packaging (other than euro pallets). To illustrate this in the context of different types of freight going in different directions, see Figure 5.

Figure 5. The figure illustrates the cargo hold of one truck, once while going North (typically with consumer goods) and going South (usually with raw materials or paper products)

Based on consultations with experts (particularly Expert 1), our compatibility matrix assumes the following properties:

Full compatibility (Scenario 1): This case exists currently, i.e., different types of general cargo can be transported in two directions (freight going between two hubs) using the same vehicle (Expert 5). We illustrate this in Figure 6.

Figure 6. Scenario 1 in which all PI-containers are compatible, i.e., do not cause any extra transportation to reposition. Compatibility could for example be achieved either through one type being foldable (as illustrated in the figure) or by several types of freight using the same boxes (c.f. Figure 8).

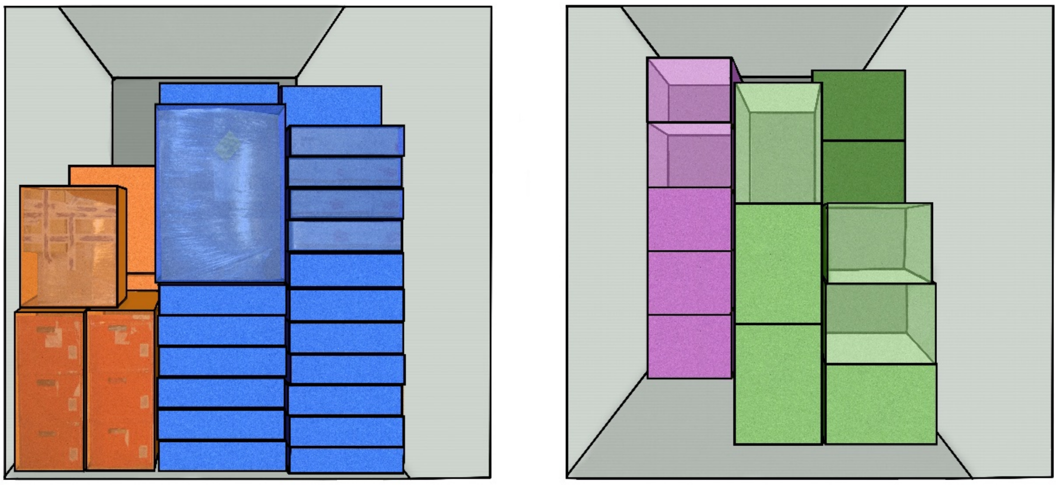


No compatibility (Scenario 2): Highly specialized PI-containers prevent integration between shipments. As an effect of PI-containers being highly specific for each type of cargo (illustrated in Figure 7).

Figure 7. Scenario 2 - no compatibility between freight groups. As there is no compatibility between PI-containers in this scenario, extra transport capacity (illustrated in the right side of

the drawing) is needed for the repositioned PI-containers. The Southbound scenario will look like Figure 7 inversed.

Northbound



Limited compatibility (Scenario 3): In this case, we assume that some of the more similar, easy-to-load freight types are compatible, whereas the others are not, thus yielding the following matrix:

Categories	1	2	3	4	5	6	7	8
Freight Types	2, 10	9, 29	6	17	23	25, 26	27, 32	33

Table 3. Freight types that can be loaded in the same PI-container for C=8 compatibility groups

In Figure 8 and Figure 9 we illustrate limited compatibility, i.e., more but not all types of freight can use the same PI-containers. Subsequently, this scenario will lead to more repositioning than in Scenario 1 (full compatibility) but significantly less than in Scenario 2 (no compatibility).

Figure 8. Scenario 3, illustrating northbound flows. As the PI-containers to a larger extent then in Scenario 2 (or 4) are compatible (can be used with) more product groups, relatively less repositioning is needed.

Northbound

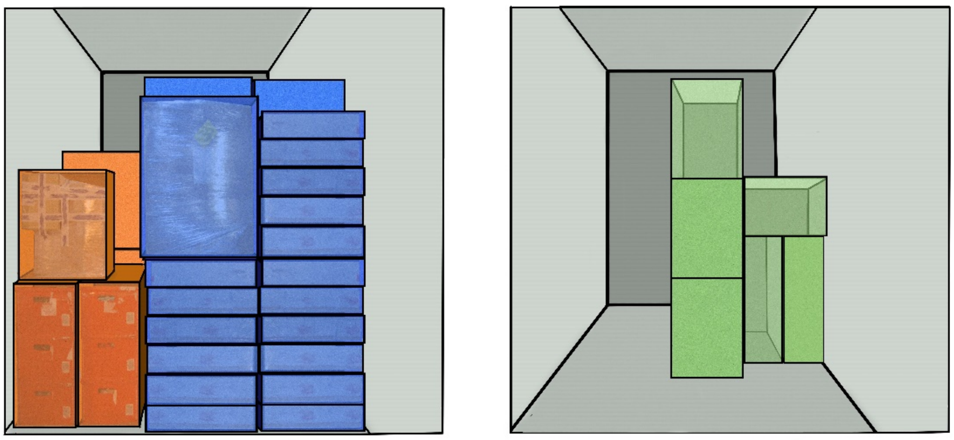
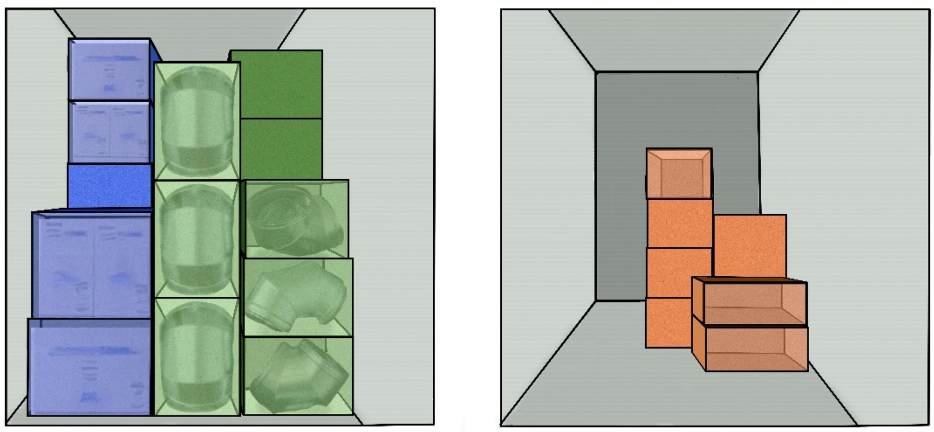


Figure 9. Scenario 3, illustrating southbound flows. See Figure 8 for explanation.

Southbound

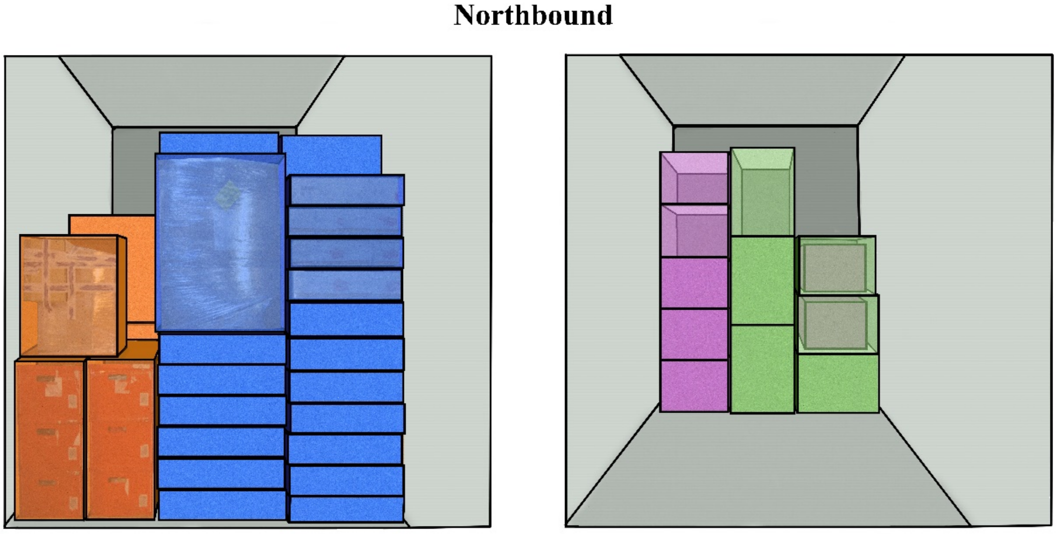


Some compatibility (Scenario 4): In this case, food, textiles, and fodder can go together; and wood, metal, and paper are compatible, thus yielding the following:

Categories	1	2	3	4
Freight Types	2, 9, 10, 29	6, 17, 26, 33	23	25, 27, 32

Table 4. Freight types that can be loaded in the same PI-container for C=4 compatibility groups

Figure 10. Scenario 4 (only Northbound) illustrated.



Assumption #7: PI uses centralized control; the conventional system does not.

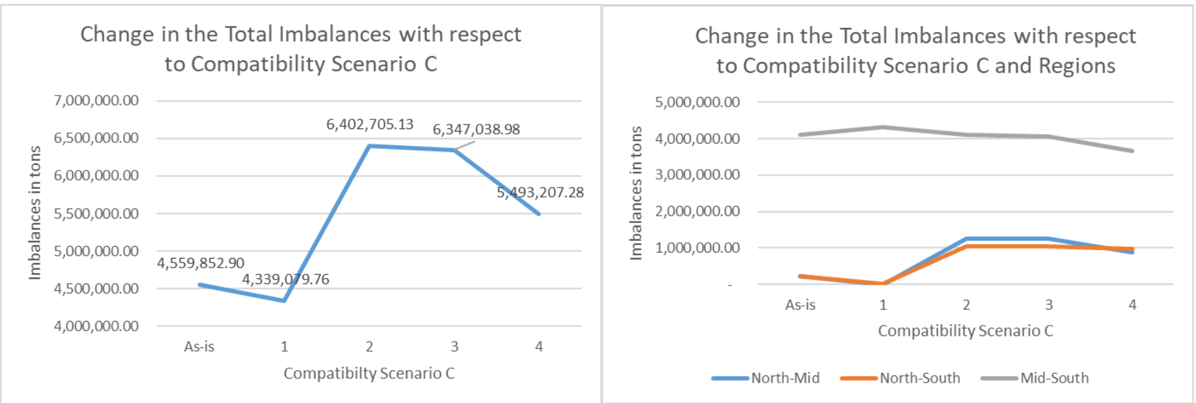
Scenario 1 represents optimization of flows in a scenario of fully compatible PI-containers. Theoretically, this scenario could apply to the centralized control of all flows in a conventional logistics network (i.e., traditional resource pooling without implementing PI). However, Simmer et al. (2017), for example, notes that actors are unwilling to relinquish control. Thus, centralized control in a conventional logistics system is deemed unrealistic (unless the environment creates urgency towards it as in Hagebäck and Segerstedt (2004)). Experts 3 and 4 also strongly emphasized this point. Therefore, this manuscript focuses only on scenarios with PI implemented.

RESULTS

In this section, we provide the results of the models using inter-regional freight data from Sweden's diverse Northern, Middle, and Southern regions. Our dataset contains 12 freight types transported among three main regions (hubs).

Figure 10 presents the results for total imbalances for all compatibility scenarios compared to each other.

Figure 11. Results for total flow imbalances.



As noted in Figure 10, compatibility makes a significant difference in the total flow imbalances. In current practice, freight is transported on pallets that can be loaded in the same container. The imbalances are the second lowest (As-is) among all scenarios, probably because there is no centralized optimization. The optimized value (C=1) is lower than the as-is case. The highest imbalance is observed when the PI-containers are not compatible, C=12. Scenarios 2 and 3 for C=8 and C=4, respectively, follow a declining pattern as compatibility increases.

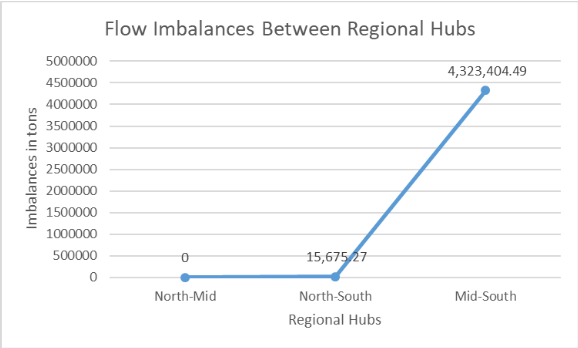
In Figure 10's right-hand graph, the imbalances are spread across the regions. The imbalance between the Southern and Middle regions is the highest. Trade between these two regions accounts for the most in the country. Interestingly, the as-is practice and the optimal (C=1) scenario results are reversed with the real practice leading to lower imbalance between the Southern and Middle regions although the optimal, C=1 is the lowest throughout all the regions, as expected. Recall that the optimization involves all the regions. The results for each compatibility scenario are as follows: C=1 representing, unchanged service modularity; and C=4, C=8, and C=12 representing, decreasing modularity.

In the LP model, we use *tons* as the unit of transportation and therefore the model solution provides the imbalances between different regions in tons. One may, however, be interested in knowing how many PI-containers needs repositioning. If the PI-container size (how much weight of a product category it is carrying), based on the imbalances in tons, the number PI-containers that need repositioning can be calculated. Note that each compatibility group can be directly associated with a different size of PI-container. This does not mean that different sizes of PI-containers cannot be used for the same compatibility group. In this case we need to assume an average PI-container size if there is a need to compute the number of PI-containers to be repositioned. Our LP model assumes the best fill-rates and does not place a restriction on the PI-container size. If the actual fill rates are lower, then the need for empty PI-container repositioning will be higher. In Appendix C, we present the number of PI-containers to be repositioned under each scenario based on the total imbalances presented in Figure 10.

Scenario 1: *C*=1

When *C*=1, we assume that PI-containers are universally compatible and interchangeable for all freight types (as with today's general cargo). Addressing the Physical Internet as Montreuil (2011) intended, this best-case scenario can aggregate all flows when calculating flow imbalances. Our results with inter-regional data from Sweden yields the minimized total imbalance as 4,339,079.76 tons of freight (See Figure 10), which is equivalent to 173,564 truck hauls, each carrying 25 tons of net freight. The imbalances among regional hubs represent 7.6% of the total transport activity (of 57,157,318.12 tons); these imbalances are shown in Appendix B, and a graphical representation is provided in Figure 11.

Figure 12. Flow imbalances between regional hubs in Sweden for Scenario 1 C=1.

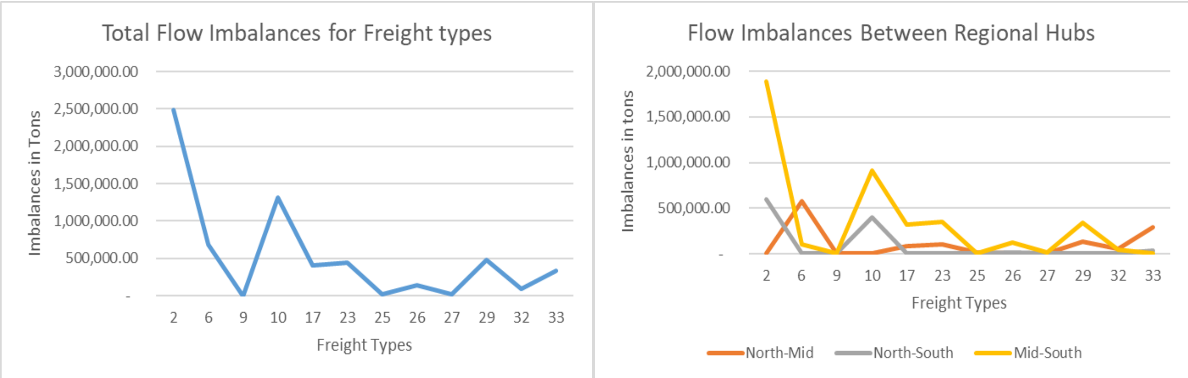


A comparison of the minimized imbalances (4,339,079.76 tons or 7.6%) and those in the as-is flows (4,559,852.90 tons or 8%, calculated using the as-is flow data) reflects the improvement potential of using optimization to determine the flows between the PI-hubs.

<u>Scenario 2: *C*=12</u>

In Scenario 2, we assume there is no compatibility between the freights in terms of the PI-containers, meaning that different freight types (see Table 1) cannot be carried in the same PI-containers and that the logistics service becomes less modularized. Thus, it is the worst-case scenario. Our results show that the total flow imbalance is 6,402,705.13 tons (see Figure 10), translating to 256,109 trucks that can carry 25 tons. The total freight carried is 57,157,318.12 tons. Therefore, the imbalances represent 11.2% of the total transportation activity. The detailed imbalances between regional hubs are shown in Appendix B, and a graphical representation is provided in Figure 12.

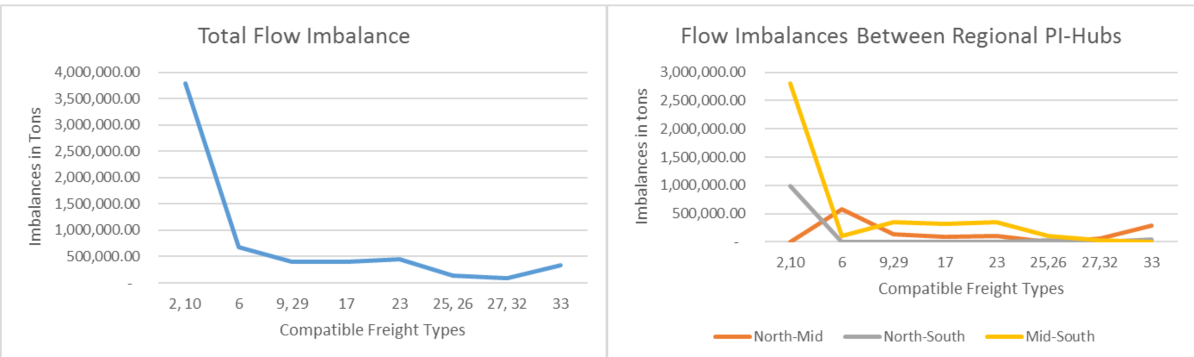
Figure 13. Imbalances for freight types for Compatibility Scenario 2 C=12.



<u>Scenario 3 *C*=8</u>

In Scenario 3, we are assuming partial compatibility between freight types shown in Table 3. We have eight groups of freight; the types of freight in each group are compatible with each other and can share the same PI-containers. Our results show that the total flow imbalance is 6, 347,038.98 tons (see Figure 10), translating to 253,882 trucks that can carry 25 tons. The total freight carried is 57,157,318.12 tons. Therefore, the imbalances represent 11.1% of the total transportation activity, not significantly different from Scenario 2. Reducing to 8 compatible groups from 12 (no compatibility scenario) did not have a big impact. The detailed imbalances between regional hubs are shown in Appendix B, and a graphical representation is provided in Figure 13.

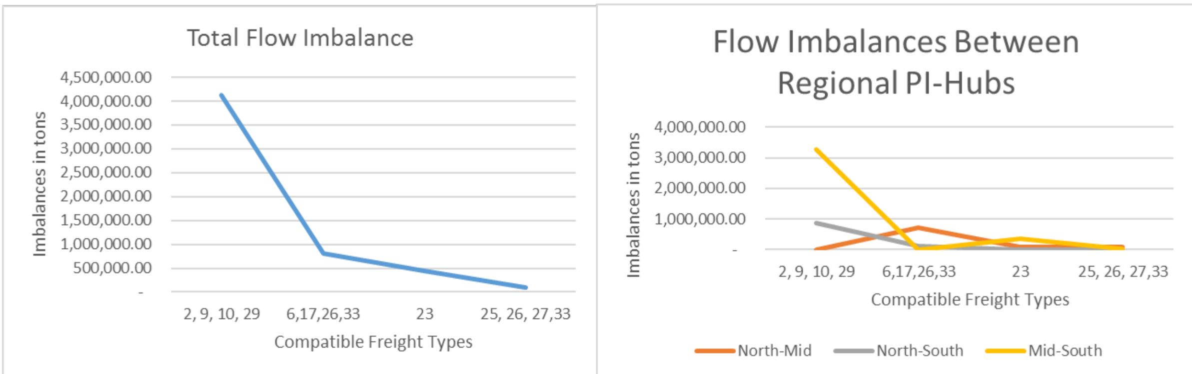
Figure 14. Imbalances for freight types for Compatibility Scenario 3 C=8.



Scenario 4 C=4

In Scenario 4, we assume that there are more compatible freight types than in Scenario 3. Based on the grouping in Table 4, we have four groups of freight such that the types in each group are compatible with each other and can share the same PI-containers. In this case, the total imbalances are 5,493,207.28 tons (see Figure 10) and 219,728 25-ton trucks. These imbalances represent 10% of the total freight. As the freight becomes increasingly more PI-container compatible, the imbalances decrease. However, the minimum is in Scenario 1 corresponds to 7.6% of all the freight transports in Sweden, thus suggesting that the imbalances between the regions in terms of supply and demand for different commodity types will still require reverse flows of empty containers, accounting for 7.6% of the total logistic activity on the highways. The detailed imbalances between regional hubs are shown in Appendix B, and a graphical representation is provided in Figure 14.

Figure 15. Imbalances' for freight types for Compatibility Scenario 4 C=4.



As shown in Figures 6 to 8, the highest imbalances are for freight types or compatibility groups that include food items 2 and 10. Again, the highest imbalances are between the Southern and Middle regions.

To determine if changes in the input data affect results, we also conducted a sensitivity analysis by considering the following modifications in demand for different freights and regions:

- The demand in the three hubs (South, Middle, and North) was reduced by 10%, 7.5%, and 5%, respectively (considering the model's general sensitivity).
- There was no reduction for freight types 2 and 10 (food), 10% reduction in all other types.
- The demand in the three hubs (South, Middle, and North) was increased by 10%, 7.5%, and 5%, respectively (considering the model's general sensitivity).

The original data was obtained under regular economic conditions. We assumed that the demand may increase (economic boom) or decline (economic recession). Accordingly, we first considered the case in which demand declines in all regions in certain proportions based on the goods demanded in those regions. Second, assuming the demand for food items remains the same even during a recession, we considered demand reductions for all items other than food. Third, we considered the case where demand increases due to an economic boom. Due to space considerations, the results of those assumptions can be found in Appendix D.

IMPLICATIONS AND DISCUSSION

Responding to several calls for research, this study has analyzed the Physical Internet using empirical data and realistic assumptions based on input from the literature and industry experts. We have focused on analyzing the potential effects of differing levels of heterogeneity of inputs, determined by the PI-containers' compatibility. Our analysis reveals a best-case imbalance of 7.6%, which is an improvement compared to the imbalances of today's conventional logistics system. If the packaging compatibility between PI-containers can be maintained (as in Scenario 1) and if automation's benefits in terminals enabled by the PI-containers can be reaped, the synergistic specificity will be low. Furthermore, major stakeholders' urgency to promote modularization through the Physical Internet will increase, because PI will be one of technology's enablers, operationalizing optimization. In the best-case (Scenario 1), PI represents a desirable vision of future supply chains.

The best-case scenario's imbalance (7.6%) should be compared to the 11.2% and 11.1% imbalances in the scenarios, where PI-containers lack compatibility (Scenarios 2 and 3, respectively). Lack of compatibility between PI-containers will cause synergistic specificity against the Physical Internet's modularization and implementation because the concept will potentially fail to deliver on improving fill rates. Compared with Scenario 1, Scenario 2 represents an additional 82,545 truckloads per year between the North and South regions, representing a substantial extra cost for shippers and an increased negative logistics environmental impact. Interestingly, Scenarios 2 and 3 differ little in terms of effect on the total freight volumes. However, as the inputs' relative heterogeneity decreases in Scenario 4, the total imbalance decreases to 10%.

Critique and future research

Our analysis has been based on seven assumptions, including that logistics services' heterogeneous demands will remain constant. However, future research is recommended to assess the validity of that assumption, as well as the others, through Physical Internet pilot trials, multiple case studies, or survey-based research.

The mathematical model we have presented in this paper addresses the PI-container repositioning problem at a strategic, aggregate level between the PI-hubs. Due to its strategic nature, this paper does *not* incorporate the problem's operational details (e.g., how the PI-containers are loaded with goods to minimize the number of PI-containers needed, how the transport containers are loaded with the PI-containers, the time for loading/unloading the PI-containers in the transport containers as well as the transport containers into the trucks, and how the trucks are routed between the PI-hubs. Including these details would enable the model to provide solutions for other operational problems in the PI. The models available in the traditional maritime container repositioning literature can be a basis for developing models incorporating the new features of PI-container repositioning. Such models will be not only large due to introducing new variables and constraints to address the problem's previously mentioned details but also more difficult to solve, especially when integer/binary variables typical in such modeling are involved. These factors will emphasize the need to develop efficient solution procedures that can solve such models intended for central PI-planning on a daily basis. Such models could potentially include first- and last-mile problems as well as the relationship to crowd logistics (Carbone et al. 2017; Castillo et al. 2018). Chen and Pan (2015) and Rai et al. (2017) have suggested investigating PI as a way to manage crowd logistics.

This paper illustrates the importance of continued research on PI-containers, taking into consideration modularity theory and inputs' heterogeneity. Future research projects must intensify design efforts for PI-containers if the Physical Internet is to maintain its position as a sustainable vision of the future's logistics. We propose inter-disciplinary design science research to address this urgent research and development gap. Furthermore, such research efforts must address the compatibility between continents because a logistics system designed only for the European market might increase inefficiencies in international transportation. Given the packaging system's importance, research is needed on how an industry-wide packaging system could be adopted (e.g., by studying the secondary industry-wide packaging systems that have been adopted across Scandinavia).

Theoretical implications

This paper contributes to midrange theory of contextualized logistics service modularization (Brax et al. 2017; de Blok et al. 2014) by analyzing modularization's strategic effects in the Physical Internet. It also contributes to the growing literature on the Physical Internet by showing the applicability and usefulness of operationalizing modularity theory applied to logistics services. Based on mathematical modelling and modularity theory, our findings emphasize the importance of logistics service modularization without increasing the inputs' heterogeneity.

Research on the Physical Internet is only in its nascent stages and much work remains. Our analysis, as well as the future research directions we offer, highlights the importance of considering packaging design in modularizing logistics and transportation, and even more so in the context of the Physical Internet.

The findings show that if the components are well designed, the Physical Internet can potentially reduce imbalances through optimizing freight flows and PI-container repositioning. However, it can also increase imbalances. PI is essentially modularization but can paradoxically result in less compatibility of logistics services if the PI-containers are not well designed. This paradox should be considered in future research on the Physical Internet's effects.

Practical implications

For the Physical Internet to become a reality, huge investments by both public and private stakeholders will be necessary. Our model presents a valuable tool for policy-makers in assessing the benefits of PI implementation. Furthermore, we make a significant contribution in guiding funding agencies about PI topics vitally important to future implementation.

Policy makers are reminded of their role in creating the urgency necessary to promote modularization. The European Commission is advised that pushing for policies that decrease the urgency to modularize (by promoting strategies easing extensive use of low-cost carriers) and simultaneously investing in implementing the Physical Internet will unlikely yield the desired effects, comparable to how low-cost production prevented large-scale manufacturing modularization (Starr 2010).

By using our research insights, practitioners should be able to have an objective view of PI-containers' potential effects in their supply chain. As exemplified in our analyses, adopting PI-containers can have either a positive or a negative impact on freight balances, depending on the PI-container design.

PI represents significant efficiency gains, but any new packaging system involves a trade-off for managers. Adopting packaging that enables automation could be beneficial unless the gains are offset by the packaging's expensive repositioning. Managers are advised to closely follow PI's development and, specifically, the proposed PI-container system's compatibility because of its effect on the efficiency.

NOTES

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APPENDIX A: LINEARIZATION OF MODEL PI^C

To linearize the objective function in Model MI, we define the following technical variables and constraints.

We define a set of technical variables as

$$t_{pij}\ for\ all\ p \in \{1, \dots, C\}, i \in \mathrm{H}, and\ j = i+1, \dots, N$$

We add the following constraints to replace constraint (4) in PI:

$$t_{pij} \geq\ fb_{pij}\ \ for\ all\ p \in \{1, \dots, C\}, i \in \mathrm{H}, and\ j = i+1, \dots, N$$

$$t_{pij} \geq\ -fb_{pij}\ \ for\ all\ p \in \{1, \dots, C\}, i \in \mathrm{H}, and\ j = i+1, \dots, N$$

Note that since t_{pij} are technical variables, there is no definition in terms of the problem's characteristics. The linearized model PI^C–L can then be formulated as

PI^C–L

$$Min \sum_{p=1}^{C} \sum_{i=1}^{N} \sum_{j=i}^{N} t_{pij}$$

subject to

$$\sum_{j=1}^{N} X_{pij} \leq \sum_{k \in F^p} S_{ikp}\ \ for\ all\ i\ and\ p \in \{1, \dots, \mathrm{C}\}$$

$$\sum_{i=1}^{N} X_{pij} = \sum_{k \in F^p} D_{jkp}\ \ for\ all\ j\ and\ p \in \{1, \dots, C\}$$

$$t_{pij} \geq\ fb_{pij}\ \ for\ all\ p \in \{1, \dots, C\}, i \in H, and\ j = i+1, \dots, N$$

$$t_{pij} \geq\ -fb_{pij}\ \ for\ all\ p \in \{1, \dots, C\}, i \in H, and\ j = i+1, \dots, N$$

$$X_{kij}\ \geq 0\ \ for\ all\ k \in F^C\ and\ i, j \in H$$

$$fb_{kij}\ unrestricted\ \ k \in F^C\ and\ i, j \in H$$

Note that we use PI^C–L in our experiments.

APPENDIX B

This appendix provides the results in more detail for the total flow imbalances of the four scenarios we simulated using our mathematical model. The number in parenthesis are the negatives of the imbalance in the opposite direction. For instance, in *Table 5* the imbalance between North and South is 15,675.27 indicating that North sends that much more freight (in tons) to South. Therefore the imbalance between South and North is (15,675.27) indicating that South sends that much less freight (in tons) to North.

Table 5. Flow imbalances between regional hubs in Sweden for Scenario 1 C=1.

From/To	**North**	**Middle**	**South**
North	-	-	15,675.27
Mid	-	-	4,323,404.49
South	(15,675.27)	(4,323,404.49)	-

Table 6. Flow imbalances between regional hubs in Sweden for Scenario 2 C=12.

Freight Type	From/To	North	Middle	South
2	North	-	-	593,224.25
	Mid	-	-	1,887,794.49
	South	(593,224.25)	(1,887,794.49)	-
6	North	-	(577,627.15)	-
	Mid	577,627.15	-	106,659.86
	South	-	(106,659.86)	-
9	North	-	-	15.94
	Mid	-	-	5.06
	South	(15.94)	(5.06)	-
10	North	-	-	396,501.19
	Mid	-	-	914,356.22
	South	(396,501.19)	(914,356.22)	-
17	North	-	84,064.81	-
	Mid	(84,064.81)	-	(317,317.87)
	South	-	317,317.87	-
23	North	-	(99,093.37)	-
	Mid	99,093.37)0	-	345,368.23
	South	-	(345,368.23)	-
25	North	-	12,148.84	-
	Mid	(12,148.84)	-	(5,328.56)
	South	-	5,328.56	-
26	North	-	-	12,500.91
	Mid	-	-	125,393.69

Freight Type	From/To	North	Middle	South
	South	(12,500.91)	(125,393.69)	-
27	North	-	-	9,248.68
	Mid	-	-	11,797.78
	South	(9,248.68)	(11,797.78)	-
29	North	-	(134,150.75)	-
	Mid	134,150.75	-	341,745.08
	South	-	(341,745.08)	-
32	North	-	50,500.36	-
	Mid	(50,500.36)	-	(46,203.59)
	South	-	46,203.59	-
33	North	-	(294,976.84)	(36,681.61)
	Mid	294,976.84	-	-
	South	36,681.61	-	-

Table 7. Flow imbalances between regional hubs in Sweden for Scenario 3 C=8.

Freight Type	From/To	North	Middle	South
2, 10	North	-	-	989,725.44
	Mid	-	-	2,802,150.71
	South	(989,725.44)	(2,802,150.71)	-
6	North	-	(577,627.15)	-
	Mid	577,627.15	-	106,659.86
	South	-	(106,659.86)	-
9, 29	North	-	(134,134.81)	-
	Mid	134,134.81	-	341,766.08
	South	-	(341,766.08)	-
17	North	-	84,064.81	-
	Mid	(84,064.81)	-	(317,317.87)
	South	-	317,317.87	-
23	North	-	(99,093.37)	-
	Mid	99,093.37	-	345,368.23
	South	-	(345,368.23)	-
25, 26	North	-	-	24,649.75
	Mid	-	-	107,916.28
	South	(24,649.75)	(107,916.28)	-
27, 32	North	-	59,749.04	-
	Mid	(59,749.04)	-	(25,157.13)
	South	-	25,157.13	-
33	North	-	(294,976.84)	(36,681.61)
	Mid	294,976.84	-	-
	South	36,681.61	-	-

Table 8. Flow imbalances between regional hubs in Sweden for Scenario 4 C=4.

Freight Type	From/To	North	Middle	South
2, 9, 10, 29	North	-	-	855,590.63
	Mid	-	-	3,278,051.60
	South	(855,590.63)	(3,278,051.60)	-
6, 17, 26, 33	North	-	(703,274.86)	(109,445.02)
	Mid	703,274.86	-	-
	South	109,445.02	-	-
23	North	-	(99,093.37)	-
	Mid	99,093.37	-	345,368.23
	South	-	(345,368.23)	-
25, 27, 32	North	-	-	24,649.75
	Mid	-	-	107,916.28
	South	(24,649.75)	(107,916.28)	-

APPENDIX C

We present the number of PI-containers to be repositioned based on the assumption that every PI-container carries 20.42kg and weighs 4.5kg, as outlined under Assumption 3 in the main text.

Table 9. Total Imbalances in tons between regions for each of the different Scenarios (As-is, 1, 2, 3 and 4).

Regions	Compatibility Scenarios				
	As-is	1	2	3	4
North-Mid	220,773.15	-	1,252,562.11	1,249,646.01	874,266.11
North-South	236,448.42	15,675.27	1,048,172.59	1,051,056.80	965,035.65
Mid-South	4,102,631.34	4,323,404.49	4,101,970.43	4,046,336.16	3,653,905.52

Table 10. Number of PI-containers to be repositioned based on the imbalances given in Table 9, and assuming that a PI-container carries 20.42kg of freight.

Regions	Compatibility Scenarios				
	As-is	1	2	3	4
North-Mid	10,811,613.5	-	61,339,966.2	61,197,160.3	42,814,207.4
North-South	11,579,256.4	767,642.9	51,330,684.9	51,471,929.6	47,259,336.5
Mid-South	200,912,406.5	211,724,020.0	200,880,040.8	198,155,541.7	178,937,586.6

Table 11. Total weight (in tons) of empty containers to be repositioned given the number of PI containers in Table 10 and assuming that a PI container weighs 4.5kg,

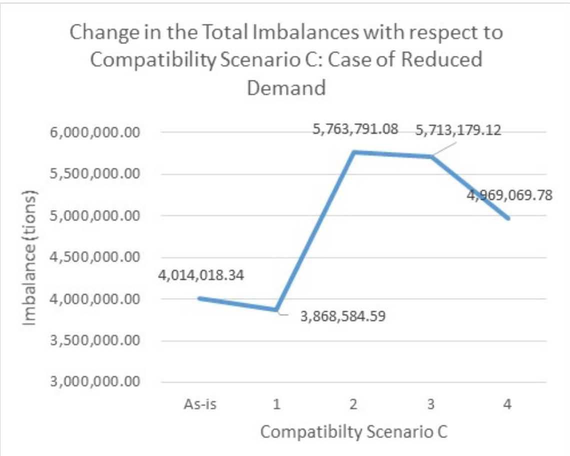
Regions	Compatibility Scenarios				
	As-is	1	2	3	4
North-Mid	48,652.3	-	276,029.8	275,387.2	192,663.9
North-South	52,106.7	3,454.4	230,988.1	231,623.7	212,667.0
Mid-South	904,105.8	952,758.1	903,960.2	891,699.9	805,219.1

APPENDIX D

We carried out sensitivity analysis to determine whether the patterns we observe would change if there are changes in the demand. The original data was obtained under regular economic conditions. We assumed that the demand may decline during economic recessions. Accordingly, we first considered the case in which demand declines in all regions in certain proportions based on the goods demanded in those regions. Second, assuming the demand for food items remains the same even during a recession, we considered demand reductions for all items other than food. Third, we considered the case where demand increases due to an economic boom. The specific increase or decrease in demand that we consider are as follows:

- The demand in the three hubs (South, Middle, and North) was reduced by 10%, 7.5%, and 5%, respectively (considering the model's general sensitivity).
- There was no reduction for freight types 2 and 10 (food), 10% reduction in all other types.
- The demand in the three hubs (South, Middle, and North) was increased by 10%, 7.5%, and 5%, respectively (considering the model's general sensitivity).

The results with modified demand show very similar patterns to the results with original demand in all three cases as shown in Figures 15-17.



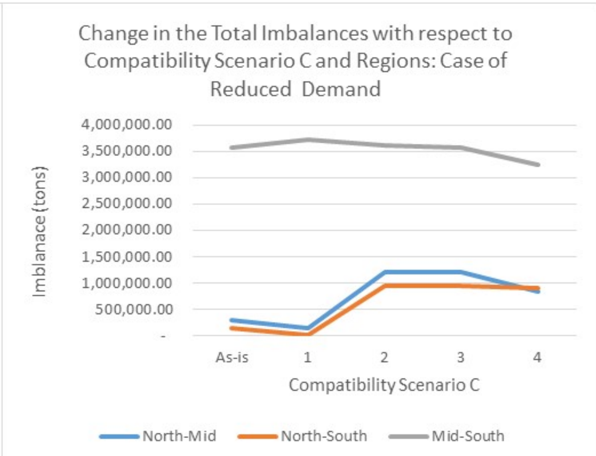


Figure 16. Results from running the model with reduced demand to simulate economic downturns for all freight types. The reduced demands have an impact on the amount shipped between the regions and the levels of PI-container flow imbalances.

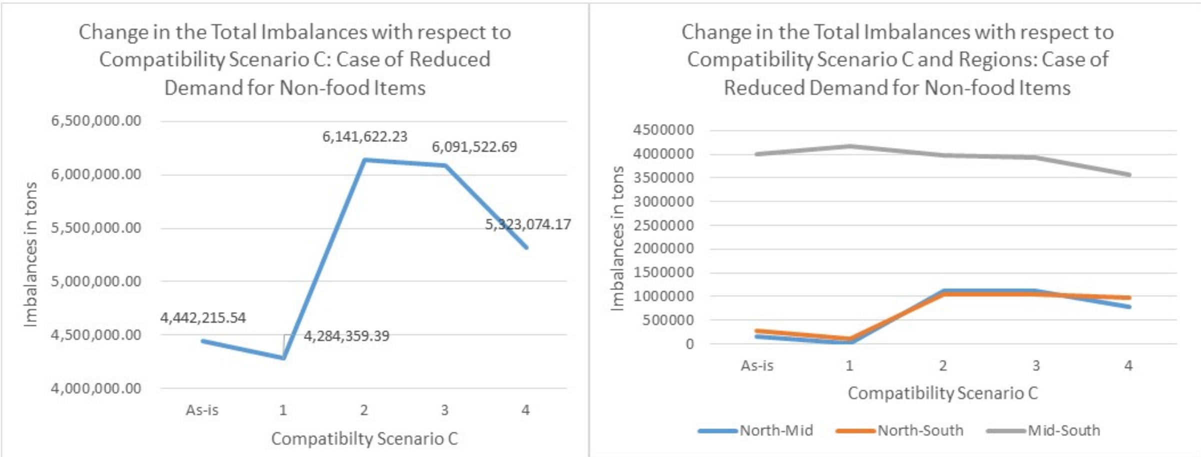


Figure 17. Results from running the model with reduced demand to simulate economic downturns for non-food items, assuming that the demand for food items will not be affected from economic downturns. The reduced demands in non-food items still have an impact on the amount shipped between the regions and the levels of PI-container flow imbalances.

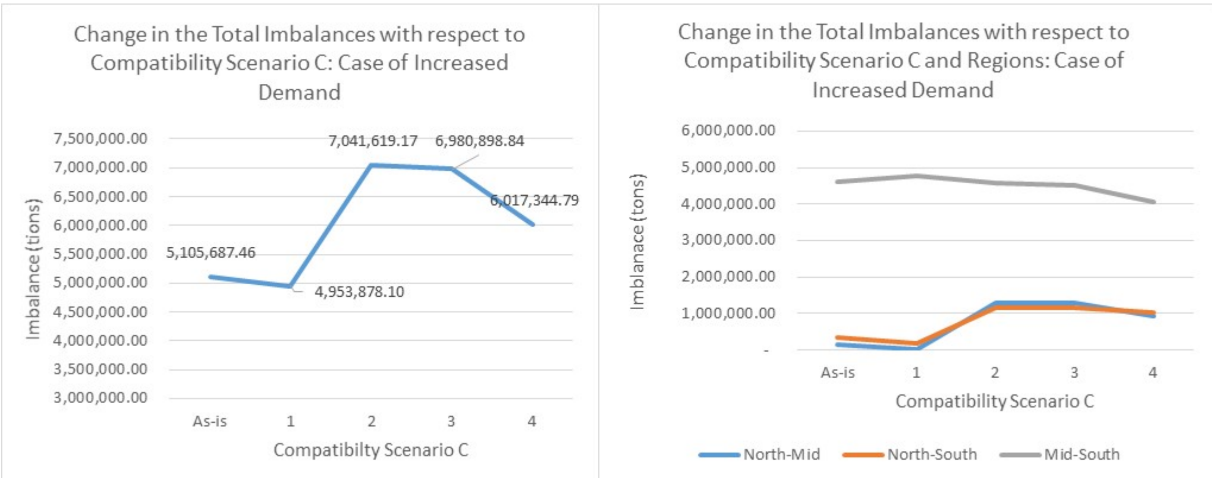


Figure 18. Results from running the model with increased demand to simulate economic boom for all freight types. The increased demands have an impact on the amount shipped between the regions and the levels of PI-container flow imbalances. The patterns based on compatibility scenarios (C=1 ,2 ,3 ,4) remain the same.