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The Physical Internet – review, analysis and future research agenda

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Abstract

Purpose – The Physical Internet (PI) is an emerging concept that applies the Digital Internet as a design metaphor for the development of sustainable, interoperable and collaborative freight transport. With the aim of aiding researchers and policy makers in their future efforts to develop efficient logistics systems, the purpose of this paper is to present a review of the existing literature on the PI, to critically discuss the concept and to outline a research agenda.
Design/methodology/approach – The literature review investigates scientific papers, project reports, specifications and other publications related to PI. In total, 46 publications were finally analyzed. The approach used in this paper is technology adoption by firms. The authors examine the PI based on four factors: organizational readiness (technological blueprints), external pressure (promised effects), perceived benefits (business model) and adoption.
Findings – A growing number of strategies, blueprints and specifications have been developed for PI, yet there are no currently developed models that illustrate how the move from the entrenched logistics business models to the PI could ensue. There is a lack of understanding of the business models needed that can involve critical actors and promote the adoption of the PI concept.
Research limitations/implications – While using the internet as a metaphor for reimagining physical transports is certainly exciting, this review and analysis suggest that several research questions need to be addressed before further PI blueprint work is carried out.
Practical implications – The "grand challenge" of sustainability in logistics needs to be addressed and improved, but the authors' analysis suggests that, to some extent, it is uncertain how the PI will contribute to improving sustainability, and why logistics service providers should engage in PI. Policy makers and practitioners are provided with critical issues to consider in the practical development and adoption of the concept.
Originality/value – This paper provides an outsider and technology-adoption perspective of PI research, as well as important implications for policy makers and researchers.

Keywords Business model innovation, Grand challenge, Autonomous logistics, Intelligent Cargo, Open logistics, Physical Internet

Paper type Literature review

Introduction

Logistics today is not environmentally and socially sustainable. Freight transportation accounts for 7 percent of global greenhouse gas emissions (Stern, 2008) and cost efficiency is often achieved by drivers working under poor social conditions (Belzer, 2000; Hilal, 2008). Freight transport operations are characterized by a low level of innovation (Wagner, 2008; European Commission, 2011), and uncertainties in various macro and micro factors cause inefficiencies (Sanchez-Rodrigues *et al.*, 2008). Addressing this global unsustainability has been termed the global logistics sustainability grand challenge (Montreuil, 2011) and in a recent issue of *Science*, Mervis (2014) describes the innovative concept, the Physical Internet

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(PI or in connection with logistics terms, π), as a future solution to the sustainability challenges of logistics.

What is the PI? In 2011, Benoit Montreuil (2011) published the first paper on the topic. He uses the Digital Internet as a metaphor for a future logistics system and Ballot *et al.* (2014, loc. 540) define the PI as:

> A global logistics system based on the interconnection of logistics networks by a standardized set of collaboration protocols, modular containers and smart interfaces for increased efficiency and sustainability.

Mervis (2014) goes on to state that, "The Physical Internet would move goods the way its namesake moves data" (p. 1104). The internet moves data by standard protocols that encapsulate the data. The PI would move freight encapsulated in designated π-containers acting as globally standardized packaging; that is, all goods, regardless of their shape, will be packaged into rectangular packaging that can dock into other packages. The concept relies heavily on modularity (see e.g. Baldwin and Clarke, 1997; Salvador, 2007) including architecture, interfaces and standards to move logistics to the next level. The Digital Internet is fully interoperable between all providers and in a similar fashion, the PI builds on horizontal collaboration, between decentralized public and private actors, using standard technical protocols (Nickerson and zur Muehlen, 2006).

As early as 2000, Klaus discussed how e-commerce would lead to an integration of actors that in the end will result in logistics functions becoming an integrated part of e-commerce. He proposed that e-commerce would eventually evolve into something called the "Material Internet" (in German: "Materielles Internet"), a concept very similar to the PI (Klaus, 2000). Over the past two decades, an even larger number of researchers have introduced and discussed a variety of logistics concepts related to the PI, such as supply chain pooling (Pan *et al.*, 2013), internet of things/intelligent products (Meyer *et al.*, 2009), hybrid shipment control (Arnäs *et al.*, 2013) and Intelligent Cargo/smart goods (Lumsden and Stefansson, 2007; Scholz-Reiter *et al.*, 2009; Sternberg and Andersson, 2014). Considering the similarities in decentralized decision making (hub level) between Intelligent Cargo and the PI, Arnäs *et al.* (2013) outlined both hybrid shipment control and smart goods as precursors to the PI. However, despite attracting substantial interest in academia, these types of information communication technology-driven freight concepts have had, to date, an insignificant practical impact (Sternberg and Andersson, 2014).

In recent years, the group of people and organizations developing and supporting the vision of the PI has grown rapidly, particularly in Europe (Treiblmaier *et al.*, 2016; Pan *et al.*, 2017). The stakeholder group, the European Technology Platform Alliance for Logistics Innovation through Collaboration in Europe (ETP-ALICE or ALICE), was formed to align stakeholder interests (ALICE, 2017). The ALICE consortium has prepared extensive plans on how to reach the vision of the PI in 2050 by a comprehensive set of roadmaps aimed at influencing research financers, such as the European Commission. The Commission currently is supporting the PI by allocating about four million euro[1] in funding for research on its potential.

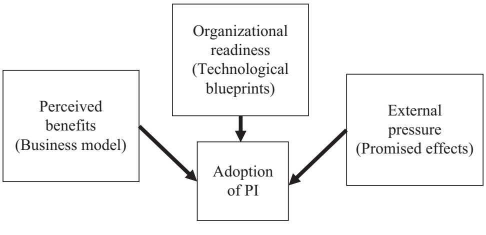
Regardless of the scientific approach to knowledge creation in logistics (Arlbjørn and Halldorsson, 2002), there is a need to understand the basis of the concepts discussed. As is often the case with bold new visions of future digital innovation in the transport industry, there is a dearth of practical and empirically grounded experiences of the PI (Pan *et al.*, 2017). The ramifications of its introduction and operations are unknown since there are none to study.

Previous research and reviews of the PI have emphasized and highlighted the positive effects of the concept (Treiblmaier *et al.*, 2016; Pan *et al.*, 2017). Pan *et al.* (2017, p. 2603) describe the PI as "a recent concept of breakthrough innovation aiming to improve by an order of magnitude the economical, environmental and societal efficiency and sustainability of the way physical objects are moved, deployed, realised, supplied, designed and used." To the best of our knowledge, the review presented in this paper represents the first critical review of the concept, scrutinizing the underlying assumptions of the PI research. The PI is a promising concept and its establishment is the aim of major policy efforts (ALICE, 2017). But what do we actually know about it? Is the PI likely to be adopted and will it be able to tackle the grand sustainability challenge of logistics? Given the intensified research efforts and the large stakeholder interest in the PI, from both public and private actors, the purpose of this paper is to present a review of the existing literature on the PI, to critically discuss the concept, and to outline a research agenda. The aim is to increase the understanding and status of the concept by critically examining the research efforts carried out so far. In so doing, the aim is also to aid researchers in their future efforts and policy makers and practitioners in their freight transport strategizing on the development (or not) of PI and its adoption.

Adoption in this context is the decision by an organization or individual to utilize and implement a concept or a technology (Oliveira and Martins, 2011). Technology adoption has been studied for decades (Oliveira and Martins, 2011), with foundational work carried out by Rogers (1962, 2003) and Tornatzky and Fleischer (1990). In essence, the PI involves modular packaging and an inter-organizational information system that enables full interoperability between all actors (Montreuil, 2011). Hence, to analyze the adoption of the PI in this review, we selected the information systems approach presented in the literature on technology adoption.

Iacovou *et al.* (1995) built on the work of Rogers (1962) and Tornatzky and Fleischer (1990), by analyzing technology adoption by firms in inter-organizational contexts and found that three factors determine the likelihood of adoption: perceived benefits, organizational readiness and external pressure. Iacovou *et al.* (1995) state that perceived benefits include direct savings related to internal efficiency, and indirect benefits related to the impact of the technology on business processes and relationships. We relate this to changes of business models. Organizational readiness is "defined as the availability of the needed organizational resources for adoption" (Iacovou *et al.*, 1995, p. 467). In addition to financial resources, the focus is on technological readiness and resources. We relate this to the technological blueprint of the PI. Iacovou *et al.* (1995) explain that external pressure to adopt comes from the organizational environment as promises and threats from mainly two sources: competitors and trading partners. In the current phase of the PI, society also appears to be an important stakeholder (Montreuil, 2011). According to Zhu *et al.* (2003), external pressure is a strong inhibitor when trading partners opt out of adopting an information system. Interestingly, Zhu *et al.*'s (2003) results were counterintuitive: firms that were more mature in terms of adoption because they had already implemented several information systems were less prone to adopt novel systems.

Figure 1 outlines the conceptual model we used to categorize drivers for the adoption of the PI. To analyze the PI, we reviewed how four factors were treated: its technological blueprint (organizational readiness), its promised effects (external pressure), its business models (perceived benefits for actors) and its adoption in itself.



Source: Inspired by Iacovou *et al*. (1995)

Figure 1.
Framework for review

First, an overview of the method for the literature review that was carried out is presented, along with an overview of the current research on PI. Second, more detailed findings from the literature are summarized and categorized according to the following four factors: technological blueprints, promised effects, business models and adoption. The findings of the literature review are then related to the four factors and are critically discussed. Suggestions and questions to be considered for a research agenda are presented. The paper ends with a concluding discussion.

Literature review – method and overview

Method

The practical motivation for this paper was a strategic PI project where the Swedish Transport Administration decided to produce a roadmap, aimed at policy makers and applied researchers, for research and adoption of PI and its components in the Swedish context. In addition to the literature review, the researchers have also met two of the key European stakeholders in the PI initiative and held a workshop discussing the findings of this review with Swedish stakeholders. The workshop consisted of 35 people including logistics managers, academics, consultants and representatives of local authorities.

The literature review was carried out following the guidelines of Denyer and Tranfield (2009), Rowley and Slack (2004), Seuring and Gold (2012) and Saenz and Koufteros (2015). We proceeded as follows: locate existing publications; select and evaluate contributions; analyze and synthesize data; and report on the findings in terms of a research agenda proposal. The research team, consisted of three senior researchers who collaborated and interacted on all aspects of the literature review, as recommended by Denyer and Tranfield (2009).

First, to locate literature on the PI and related concepts, the authors used the Web of Knowledge, Google Scholar, the PI website (www.physicalinternetinitiative.org) and an ancestry approach to publications (Colicchia and Strozzi, 2012). Scientific papers, reports, a doctoral dissertation and books that directly address the logistics concept "PI" were included. Some frequently referenced or complementary conference articles were included as well. Literature on the (Digital) Internet was not included in this part of the process.

Second, in order to limit the number of publications on the physical infrastructure of the internet, the string "AND" (Logistics OR Transport OR Supply OR Distribution) was added to "PI." Still, the search strings generated a large number of publications on the physical infrastructure of the internet itself, which were excluded by screening the abstracts. PI articles are easy to select because their abstracts always contain supply chain related terms, such as supply chain, logistics, distribution, freight, goods and inventory. In addition to the Web of Knowledge and Google Scholar search strings, the ancestry approach was applied using Google Scholar on papers citing Montreuil's (2011) original journal paper on the PI. Finally, we compared our review with another review of the PI by Treiblmaier *et al.* (2016) and the recent special issue on PI (Pan *et al.*, 2017), to ensure that the most relevant sources were included in our review.

In total, 46 publications using the term "PI" were selected for the review: 24 journal papers, 2 scientific magazine articles, 3 reports, 16 conference proceedings papers, 2 chapters from edited books, 1 doctoral dissertation and 1 book. Duplicates of 2 conference papers were published in scientific journals and were thus not included among the 46 publications. See Table AI for a full listing of the 46 publications.

All published journal papers and book chapters were included. We have not been fully consistent with conference papers. All conference papers published before 2014 were included, with the exception of the papers that had later versions published in scientific journals. Conference papers between 2014 and 2016 were only included if they addressed business models or adoption of the PI. The aim has been to focus on quality assured and reviewed papers, but also to capture early developments in the different areas. Research on business models and adoption of PI is clearly not as developed.

Third, we structured, analyzed and presented the content from the literature on the PI. The 46 publications were categorized based on four factors from the technology-adoption literature (Figure 1): technological blueprints (organizational readiness), promised effects (external pressure), business models (perceived benefits for the actors) and adoption of the PI.

Fourth, we developed a research agenda based on implications from the technology-adoption model.

Overview of publications

Of the 24 journal papers reviewed, 13 were published between January 2016 and May 2017, indicating a trend of continuously increasing interest in the concept.

A variety of research methods have been used in the reviewed publications (see Table I). Some papers are conceptual (e.g. Montreuil, 2011; Montreuil, Ballot and Fontane, 2012; Montreuil, Sarraj, Cimon and Poulin, 2012); others use simulation (Furtado *et al.*, 2013; Sarraj, Ballot, Pan, Hakimi and Montreuil, 2014) and/or mathematical modeling (Sarraj, Ballot, Pan and Montreuil, 2014; Tran-Dang *et al.*, 2015). Several of the analytical papers used real-life data from retailers and suppliers, in France in particular (Sarraj, Ballot, Pan, Hakimi and Montreuil, 2014).

Of the 46 publications on the PI, 33 are related to Laval University (Canada) and/or Paris Mines (France). In total, 88 authors contributed to the 46 publications reviewed, with Montreuil (Laval University) and Ballot (Mines Paristech) authoring or co-authoring 16 each, and Pan (Mines Paristech) authoring 12. Sarraj (Mines Paristech) and Yang (Mines Paristech) authored 4 publications and Hakimi, Meller and Xu authored 3 each. Six authors authored or co-authored 2 publications, the remaining 74 authors, 1 each. To conclude, a few institutions

Main method(s)	Number of applications	Publications
Mathematical modeling	12	Sohrabi and Montreuil (2011), Lin *et al.* (2014), Othmane *et al.* (2014), Colin *et al.* (2015), Kong *et al.* (2016), Qiao *et al.* (2016), Venkatadri *et al.* (2016), Yao (2016), Zhang *et al.* (2016), Fazili *et al.* (2017), Mohamed *et al.* (2017) and Yang *et al.* (2017b)
Simulation	10	Ballot *et al.* (2012), Hakimi *et al.* (2012), Arnäs *et al.* (2013), Furtado *et al.* (2013), Pan, Xu and Ballot (2014), Sarraj, Ballot, Pan, Hakimi and Montreuil (2014); Pan and Ballot (2015); Yang *et al.* (2015), Sallez *et al.* (2016) and Yang *et al.* (2017b)
Conceptual	9	Montreuil (2011), Montreuil, Ballot and Fontane (2012), Montreuil, Sarraj, Cimon and Poulin (2012), Ballot *et al.* (2013), Montreuil *et al.* (2013), Cimon (2014), Oktaei *et al.* (2014), Rougés and Montreuil (2014) and Crainic and Montreuil (2016)
Simulation and mathematical modeling	3	Pan and Ballot (2015), Walha *et al.* (2016) and Tran-Dang *et al.* (2017)
Multimethod	2	Ballot *et al.* (2014) and Hakimi (2014)
Case study and prototype design	2	Zhong *et al.* (2017) and Zhong *et al.* (2016)
Conceptual and mathematical modeling	2	Meller *et al.* (2013) and Sarraj, Ballot, Pan and Montreuil (2014)
Experiment (case study)	1	Le Roch *et al.* (2014)
Linear programming	1	Darvish *et al.* (2016)
Literature review	1	Treiblmaier *et al.* (2016)
Prototype	1	Lin and Cheng (2016)
Interviews	1	Simmer *et al.* (2017)
Product design	1	Landschutzer *et al.* (2015)
Total	46	

Table I.
Research methods applied

(that almost create a PI community) have dominated the existing academic research so far, but the concept has started to diffuse.

The contributions of most publications are primarily related to one of the four adoption factors, with the exception of the book "The Physical Internet – The Network of Logistics Networks" (Ballot *et al.*, 2014), which extensively covers all areas of PI (see Table AI). Figure 2 presents the contributions from the PI literature.

Starting in 2015, several of the included papers also focus on the inside of production plants connected to the PI (Zhong *et al.*, 2015, 2016, 2017; Lin and Cheng, 2016).

The PI – review

In this section, the main content from the literature reviewed is described in relation to the four factors of technology adoption.

Technological blueprints (organizational readiness)

Following Montreuil (2011), several authors have published on the workings of the PI. The analogy between the "Digital" and the "Physical" Internet is central to technology blueprints. Sarraj, Ballot, Pan and Montreuil (2014) address the analogy in depth, with a focus on routing from a network perspective; Montreuil, Ballot and Fontane (2012) create a mapping between the Digital Internet and PI layers by defining three interacting layers of the PI: realization web (open production, personalization and retrofit centers), distribution web (open distribution centers and warehouses) and mobility web (open unimodal and multimodal hubs and transits).

Ballot *et al.* (2014, loc. 2943) state:

> The primary fundamental component of the approach is the Physical Internet's system of modular containers. This is what will make the shared network possible. It is about assessing the real needs beyond existing conventions and specific requirements.

It is argued that most of the technologies necessary to realize the PI already exist, or will exist, in the near future. The EU project, Modular Logistics Units in Shared Co-Modal Networks (Moduluscha), has developed π-containers for the last three years. However, in the process of writing this paper, the only public specifications available were found in Landschutzer *et al.* (2015).

On a more detailed technical level, Tran-Dang *et al.* (2017) describe how to enhance the functionality of π-containers with wireless sensor networks. Sallez *et al.* (2016) analyzed and simulated π-container activeness, with an active product defined as "[…] able to identify its state, compare its state with the desired one and, when certain conditions are met, send information" (p. 99).

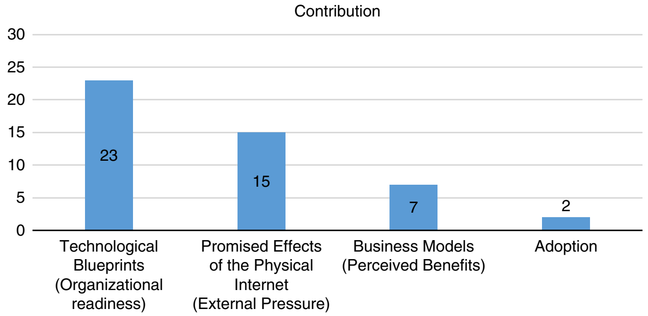


Figure 2. Contributions from the PI publications analyzed

The detailed functional designs of PI facilities are outlined in three reports: Meller *et al.* (2013) describe the design of a road-based transit center, which in terms of the internet has a switch functionality. Ballot *et al.* (2013) outline a road-rail hub; in the PI, the rail should run according to schedule, as opposed to trucks that leave a depot after being filled (some exceptions apply). Montreuil *et al.* (2013) describe the design of a unimodal road-based crossdocking hub.

Walha *et al.* (2016) addressed allocation of π-containers to destination docks. Inside the logistics center, continuous auctions should take place and Kong *et al.* (2016) proposed and analyzed dispatching rules.

Recently, some authors have expanded research on the PI beyond logistics. Lin and Cheng (2016), for example, illustrated PI-enabled production in the solar cell industry and Zhong *et al.* (2016) proposed a design of a prototype system applying the PI to the logistics of the manufacturing shop floor.

Promised effects of the PI (external pressure)

Montreuil (2011) describes 13 characteristics of the PI that address 13 unsustainability symptoms of the global logistics system, as shown in Table II.

Several other conceptual papers identify the PI as a key to tackle the grand challenge of logistics sustainability, and as an enabler of new business models (Montreuil, Sarraj, Cimon and Poulin, 2012).

The heart of the PI is achieving the potential positive effects of pooling logistics and transport resources by creating "The Network of the Logistics Networks" (Ballot *et al.*, 2014). The past two decades have seen several successful implementations of inventory pooling (Simchi-Levi *et al.*, 2007), joint distribution centers (Cruijssen *et al.*, 2007; Cruijssen *et al.*, 2010) and shared transport purchasing (Frisk *et al.*, 2010; CO3 Project, 2013). Hence, a majority of the previously published research on the potential positive effects of collaboration, cooperation and global supply chain optimization, potentially applies to the PI.

In order to refer to the potential effects of the PI, many papers and reports cite three papers: Ballot and Fontane (2010), Pan *et al.* (2013) and Pan, Ballot, Fontane and Hakimi (2014). These three papers do not specifically address effects of the PI, but rather analyze hypothetical supply chain pooling (using actual data as parameters, but without actual implementation). For example, Pan *et al.* (2013) show in a simulation how pooling supply chain resources would render great environmental and cost savings.

An experimental computation by Sohrabi and Montreuil (2011) show how an open supply web would enable strong reductions in customer service time. A mathematical model by Sarraj, Ballot, Pan and Montreuil (2014) shows how to improve the routing through the PI. Great improvements have also been the results of models by Lin *et al.* (2014) and Yang *et al.* (2015).

Simulations of the French retail supply are described in many of the publications on the PI (e.g. Hakimi *et al.*, 2012; Sarraj, Ballot, Pan, Hakimi and Montreuil, 2014; Pan *et al.*, 2015), and Ballot *et al.* (2014) offer an overview of several of the published studies (e.g. Ballot *et al.*, 2012; Hakimi, 2014; Sarraj, Ballot, Pan, Hakimi and Montreuil, 2014). All studies show great improvements to be expected through the PI: Ballot *et al.* (2012) reported a 20 percent reduction of fuel consumption; Sarraj, Ballot, Pan, Hakimi and Montreuil (2014) suggested a possible 60 percent CO_2 reduction; and Yang *et al.* (2017b) found that logistics cost might in some cases be reduced as much as 73 percent. It should be noted that none of the studies include return flows of π-containers, which would be important to consider to come up with accurate figures of the effect.

Publications such as Montreuil (2011) and Fazili *et al.* (2017) point to increased social sustainability as an effect of the PI. This is achieved by trucks returning to their point of origin. An underlying assumption seems to be that one driver statically belongs to one truck, that is, the driver returns home when the truck returns to the point of origin.

Table II. Physical Internet characteristics and unsustainability symptoms

	Physical Internet characteristics												
Unsustainability symptoms	1 Objects encapsulated in world standard modular containers	2 Universal interconnectivity	3 Container handling and storage systems	4 Smart network containers embedding smart objects	5 Distributed multi-segment intermodal transport	6 Unified multi-tier conceptual framework	7 Open global supply web	8 Product design for containerization	9 Product materialization near to point of use	10 Open performance monitoring and capability certification	11 Webbed reliability and resilience of networks	12 Business model innovation	13 Open infrastructural innovation
1 We are shipping air and packaging	●							●					
2. Empty travel is the norm		●			●								
3. Truckers have become the modern cowboys			●		●								
4. Products mostly sit idle, stored where unneeded, yet so often unavailable where needed	●			●			●						
5. Production and storage facilities are poorly used	●	●	●				●	●	●				
6. So many products are never sold, never used		●					●		●		●	●	
7. Products do not reach those who need them the most		●			●	●	●		●		●		
8. Products unnecessarily move, crisscrossing the world		●		●	●					●			●

(*continued*)

Table II.

Unsustainability symptoms	Physical Internet characteristics 1 Objects encapsulated in world standard modular containers	2 Universal interconnectivity	3 Container handling and storage systems	4 Smart network containers embedding smart objects	5 Distributed multi-segment intermodal transport	6 Unified multi-tier conceptual framework	7 Open global supply web	8 Product design for containerization	9 Product materialization near to point of use	10 Open performance monitoring and capability certification	11 Webbed reliability and resilience of networks	12 Business model innovation	13 Open infrastructural innovation
9. Fast and reliable intermodal transport is still a dream	●	●	●	●	●	●				●			●
10. Getting products in and out of cities is a nightmare	●	●		●	●	●	●		●		●		
11. Networks are neither secure nor robust	●	●		●	●		●			●	●		
12. Smart automation and technology are hard to justify	●	●	●	●		●				●		●	●
13. Innovation is strangled	●	●	●	●		●						●	●

Source: Adapted from Montreuil (2011)

Business models (perceived benefits)

Several publications outline the PI as a key driver of business model innovation. "Business models can be thought of as the way a company creates value in a competitive landscape" (Montreuil, Sarraj, Cimon and Poulin, 2012, p. 33). Montreuil, Sarraj, Cimon and Poulin (2012) divide the actors in the logistics landscape into PI-enabling firms and PI-enabled firms.

Pan, Xu and Ballot (2014) use mechanism design theory to make a business model of the logistics service providers/carriers. Every transport is auctioned, where the lowest bidding carrier wins. Auctioning and nested auctioning ("reallocation requests") are carried out by proxy agents acting according to specific parameters (e.g. cost, capacity). Transport auctions are also addressed by Qiao *et al.* (2016). In order for this process to work, near complete transparency about capacities and constraints is necessary.

Ballot *et al.* (2014, loc. 2917) write:

> In the context of the Physical Internet, business models are likely to be severely challenged. The ordering customer, or shipper, leads the transportation service provider to have no direct business relationship with the recipient. Consequently, because of the change in flow the parties involved in urban delivery are increasing, with no stakeholder able to propose consolidation of deliveries that can be invoiced to the recipients with different levels of service and where the number of deliveries to a recipient can only be accounted for in volume or weight.

Oktaei *et al.* (2014) is the only paper that conceptually discusses the business model of a transit center (from the perspective of a single operator with surplus warehouse and parking capacity), but the authors do include some services being made available based on personal communication with a customer (though it is not evident from the paper who the customers are). They suggest revenues through access services, resting services, matching services, short-term storage services and parking services, and renting extra capacity, but without proposing any figures.

Qiao *et al.* (2016) analyzed less-than-truckload dynamic pricing in the PI. They propose a "decision making model for LTL carriers in PI, to determine their optimal pricing decision and then optimise their profit" (p. 9). Cimon (2014) outlines the need for transparency in PI business models in order to avoid principle-agent issues.

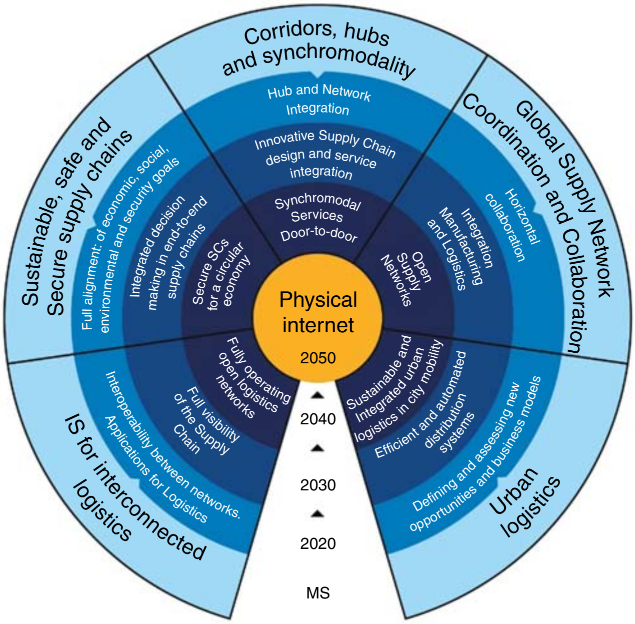
Adoption

The adoption process of the PI is not specified in any of the reviewed publications, but ALICE (2017) has created a roadmap of how the PI will gradually replace the logistics of today in line with the reasoning in Ballot *et al.* (2014). The roadmap is built on the idea that progress will follow certain developed milestones, as illustrated in Figure 3.

No research was found on how PI could gradually be adopted to replace current logistics operations, but Simmer *et al.* (2017) interviewed logistics service providers in Austria in order to identify adoption challenges:

> The majority of companies consider the external digitization, meaning the interfaces with customers, as the greatest challenge, but also data processing and standard data exchange were frequently mentioned. Further challenges, which were rarely suggested, pertain to the retention of flexibility, the capital expenditure, the scope of interconnection without interface rupture, the changes in professional profiles and the need to always have state-of-the-art technology (p. 131).

The paper by Fazili *et al.* (2017) is the only one that addresses hybrid systems, which is a PI co-existing with conventional logistics. They suggest that conventional shipments be loaded into π-containers, routed and then unloaded from the π-container before the final destination.



Source: ALICE (2017)

Figure 3.
Roadmaps toward a global implementation of the Physical Internet

Critical discussion and research agenda for the PI

Given the massive attention the concept attracts and the central role it plays in policy makers' logistics roadmaps, this section presents a critical discussion of technological blueprints, promised effects, business models and the adoption of the PI.

Technological blueprints (organizational readiness)

For different organizations (such as logistics service providers, carriers and shippers) to be ready to adopt, they must be financially and technologically ready (Iacovou *et al.*, 1995), that is, they must understand the technology. Most of the PI literature focuses on technology such as handling nodes and their unloading systems, containers and dispatching rules. The packaging system is at the heart of PI, but very little information is available outside the PI community. Blueprints of the packaging system need to address their relation to the existing entrenched package and load unit systems, such as the 20 ft container and the EU trailer. Hence, given the importance of the PI packaging system, policy makers and researchers need to address these central questions:

- What are the blueprints for the π-packaging system?
- How would the π-packaging system relate to the existing entrenched package and load unit systems, such as the 20 ft container and the EU trailer?

The second question in particular is important as history is full of technologies never adopted in favor of less optimal designs (Rogers, 2003), and because the previous adoption of technology is one of the strongest inhibitors of novel technology adoption (Zhu *et al.*, 2003).

Any well-formed theory or concept should be supported by a strong underlying logic and rationale. The PI relies heavily on the internet as a metaphor of decentralization and robust system design. Physical transportation by nature, though, is not fully digital. While design by analogy is at the core of PI, the limitations of this approach are simultaneously acknowledged in the PI literature:

> And before we get too far into this definition and how the Physical Internet is enabled, we need to note that the parallels between the Digital and Physical Internets, although significant, are not absolute. That is, information transfer protocols cannot be directly transposed to goods. The physics of information and objects are too different Ballot *et al.* (2014, loc. 547).

Digital artifacts have a number of distinct advantages. They can be duplicated without cost and sent anywhere instantly. Most importantly, they generate no return flows. The full ramifications of the centrality of these facts are not discussed in the current PI literature. Internet routing protocols lose a considerable amount of sent data (measured as "frame loss rate"), but is not considered a problem simply due to the fact that digital artifacts can be resent at virtually no cost. Given the difference between physical and digital objects, an important question to address is:

- How will reliable routing be ensured without loss of quality?

The internet started out as a non-profit infrastructure project with a low degree of complexity and was first run by the public government. This paved the way for it to become a commercial infrastructure (Nickerson and zur Muehlen, 2006). Overall, a considerable number of papers and reports address design aspects of wireless networks (e.g. Tran-Dang *et al.*, 2017), and π-facilities (Ballot *et al.*, 2013; Meller *et al.*, 2013), whereas only one conference paper addressed the need for designing governance in the PI (Cimon, 2014). Currently, most publications on PI assume that commercial stakeholders act either self-rationally or follow a central optimization. Sergio Barbarino, a principal figure in both ALICE and the PI initiative (Mervis, 2014; Pan *et al.*, 2017), stated in a conversation: "We have public transportation for people. Why should we not have public transportation for goods?" Yet, involving public actors in the building of the PI has not yet been proposed in the PI literature. Given the need for governance, we pose two further questions:

- Who will be responsible for monitoring and enforcement in the PI?
- What are the potential effects of a public freight transport system?

Promised effects of the PI (external pressure)

The PI sets out to tackle the grand sustainability challenge (Montreuil, 2011), as presented in Table II.

Balanced transport flows are key to high fill rates and sustainable freight transportation, yet freight imbalances characterize logistics in most parts of the world (Hesse and Rodrigue, 2004). In Scandinavia, the southbound flows in Norway, Sweden and Finland are very different from the northbound flows (see e.g. Vierth *et al.*, 2012). McKinnon and Ge (2006) analyzed potential backhauling in the UK and found that the incompatibility of vehicles and products was one of the major factors behind empty running. If all goods are packaged in π-containers specifically adapted for each product type (Montreuil, 2011), the containers would have to be returned to the place of origin. In the process of separating out the categories of goods that would become incompatible when the π-containers are introduced, the imbalances would increase:

- What impact would freight imbalances have on PI and its efficiency?
- What impact would the additional flows of returning π-containers have?
- How would PI handle imbalances in freight flows, when considering volatility in the flows of π-containers?

The promised effects of any innovative concept can be divided into direct and indirect effects (Iacovou *et al.*, 1995). While direct effects are easy to measure inside an organization, indirect effects occur only when technology is adopted throughout several organizations. Hence, the potential of any logistics technology has to be assessed at low penetration levels (Sternberg and Andersson, 2014) and without key trading partners opting in. Some stakeholders, such as shippers and logistics service providers, are likely to defend their business models and their ability to maintain control over their propriety networks (Iacovou *et al.*, 1995). Hence, future research on the effects of the PI needs to address:

- What will the effects of the PI (or its components) be in a time period of limited adoption in terms of geography and number of actors?
- How will the resistance of key stakeholders to implement PI business models affect the results?

Supply chains are inherently complex and in order to quantitatively analyze them, models have to be simplified to handle the complexity, for example, through data aggregation (using customer zones and/or product groups) (Simchi-Levi *et al.*, 2007). Obviously, the data aggregation needs to reduce complexity, but still reflect the nature of the system studied; product groups, for example, could be based on characteristics such as delivery methods or product family. Studies showing significant improvement from the PI need to be viewed in the light of their assumptions and simplifications. Montreuil (2011) aggregates thousands of retailer products to one product and Sarraj, Ballot, Pan, Hakimi and Montreuil (2014), Sarraj, Ballot, Pan and Montreuil (2014) and Ballot *et al.* (2012) exclude return flows of the π-containers (i.e. 50 percent of the flow). The handling and storage cost of π-containers for retailers is excluded in all studies. Hence, to properly address the impact of the PI, public and private policy makers need to answer:

- How should the levels of calculated supply chain pooling be reached in reality (considering real data, aggregated into product groups based on distribution requirements)?

Another key interest of many European stakeholders is the social unsustainability of the trucking industry. This has received increased attention in the past few years (European Commission, 2017). Drivers who spend as much as six months at a time on the roads without an opportunity to go home (Hilal, 2008) have received a lot of public attention. According to Montreuil (2011, p. 85), "Container handling and storage systems" and "Distributed multi-segment intermodal transport" address the issue of truck drivers' social unsustainability in the PI, yet it is unclear how the components in Table II actually address the grand challenge. Pan, Xu and Ballot (2014, p. 3) propose how road haulage will work:

> On one hand, new entrance requests will be allocated to the carriers offering lowest price after auction, i.e., auction-based marketplaces; on the other hand, the PI network enables carriers exchanging their capacities via auction based real-location in the π-hubs.

The PI literature does not explain how a continuous auctioning will improve social sustainability. Intuitively it might rather lead to a "race to the bottom," enhancing the trend of road haulers competing with low-wage drivers rather than efficiency (International Labour Organization, 2015). One way of tackling this potential social challenge is by introducing reputation-based auctions to the PI, as proposed by Othmane *et al.* (2014). To understand the potential adoption of the PI, several questions need to be investigated that are linked to external pressure, such as:

- How would PI reduce the social unsustainability of truck drivers?
- How would PI handle social sustainability challenges for drivers (since the concept is based on price pressure through continuous auctions)?

It is necessary for policy makers to understand the crucial environmental and social effects in order to support investments in infrastructure for the PI and to be able to generate external pressure.

Business models (perceived benefits)

As outlined in the review, the PI literature to a large extent lacks the operationalization of business models. The future of existing business models and PI business model engenders some important questions not yet addressed in the PI literature. Rhetorical questions arise such as, "Why would a logistics service provider give up the control of their transport networks, without any clear incentive to do so?" (Simmer *et al.*, 2017), and "Why would carriers want to enter a system of continuous real-time auctioning for the lowest price?" These questions are to some extent acknowledged by Ballot *et al.* (loc. 2917): "This difficulty is all the greater because it runs counter to the components that until now have been firmly anchored in the culture of logistics service providers." Without the supply chain actors opting in, the PI will remain a series of blueprints. Finally, a business model that enables the reallocation and distribution of π-containers throughout the global PI is absent. Hence, these questions need to be addressed:

- What incentives would persuade logistics service providers to give up control of their transport networks?
- Why would dominant freight companies enter into PI standardization efforts and invest in cooperation when they risk losing control and market position?
- How can the challenges of horizontal collaboration among logistics service providers in PI be overcome?
- How should the modular π-containers be widely spread and adopted so that an open network of automatic bidding hubs can be implemented?

Following the discussion on transport auctions in the previous section, two critical questions from the hauler/carrier perspective arise that require answers:

- Why should carriers enter a system of transparent continuous real-time auctioning at the lowest price?
- What should the business models be like to get carriers into auctions that focus purely on the lowest bid?

Adoption

Potential adoption is crucial to the relevance of carrying out research on a technical concept, in particular given the history of unsuccessful technology-driven logistics concepts (compare Sternberg and Andersson, 2014). Our review reveals that this crucial aspect has not yet been examined in the PI literature, with only two publications very briefly addressing adoption (Ballot *et al.*, 2014; Fazili *et al.*, 2017). In the previous sections we have outlined barriers to adoption, related to organizational readiness, external pressure and perceived benefits. Given the lack of research on adoption of PI, we suggest that future research prioritize the overarching question:

- What are the most important barriers for PI to overcome to be implemented and to make a practical impact?

The remainder of this section addresses specific adoption aspects that emerged in the review. Adoption of novel technologies is a step-by-step process. As technology maturity differs widely between continents, countries and regions, we reason that the PI will have to co-exist and interact with the conventional logistics system for years. This is not addressed in the PI literature, with the exception of Fazili *et al.* (2017). Fazili *et al.* assume that the actors will have incentives to put their load units into one of six proposed π-containers. In order to enable this type of adoption, the actors would have to consider it to be sufficiently beneficial for them to afford the additional handling costs of combining the systems; yet no business model addressing this incremental adoption is provided.

The ALICE roadmap toward the 2050 vision of PI does outline some necessary research and development steps, but not the adoption mechanisms, that is, how the concept could be disseminated. The ALICE roadmap assumes that adoption is desirable based on the stated positive effects of PI, despite the promised effects being, as outlined in this review, very unclear. In a recent interview, the Vice-Chair of ALICE, Professor Rod Franklin, suggested that a bottom-up approach to the adoption of the PI is viable:

> Maybe, but the digital internet started organically, locally, then eventually the world became connected. Cities will do the same thing with the Physical Internet. There are international groups of mayors who talk with one another. Then over time, those organic projects will begin to connect to each other. If you look at large markets like Europe, the US, and Asia – China could be the first to adopt the idea. That's a country with horrible traffic problems in its cities (Shaposhnikova, 2017).

What Franklin suggests is that the PI can enable more efficient traffic (external pressure) and that municipalities are more inclined to adopt (higher level of organizational readiness). If the bottom-up adoption approach is taken by ALICE and the PI community, we propose studying the adoption factors starting at the local level:

- What are the actual benefits, blueprints and business models that will enable the adoption of PI by municipalities or at the municipal level?

Concluding discussion

This literature review offers an overview of current research, a critical discussion and a research agenda for the PI. A contribution to current research on PI is the use of technology adoption on an organizational level, as theoretical lens for our discussion (Iacovou *et al.*, 1995).

For managers, researchers and policy makers, we recommend that before further technology blueprint work is carried out, that sustainability effects, the business models for involved actors, as well as the adoption process of the PI be thoroughly investigated. We also advise caution when interpreting studies of the coming positive effects of the PI, as the models studied in this review promote extensive simplifications, such as excluding return flows or costs for handling of containers. The outsider perspective and a balanced view (the existing research is dominated by a few institutions) of the metaphor is a contribution to practitioners and policy makers that can provide new insights for where to focus further efforts if and when they decide to continue exploring the PI.

Any empirically untested and emerging concept is likely to encompass a host of challenging hurdles to overcome before widespread adoption occurs. This review of the literature underpinning the PI concept contributes to future adoption as a number of such issues have arisen. What is crucial to understand from a shipper's or policy maker's perspective is that currently there are no well-developed models that illustrate how the move from the entrenched logistics business models to the PI could ensue.

We have also viewed the PI as a blueprint rather than a vision. Views of what the PI is differ between stakeholders. Whereas detailed technical blueprints suggest it to be an engineered system (e.g. Meller *et al.*, 2013; Montreuil *et al.*, 2013), other stakeholders describe it as a vision of all existing technologies and actors working together (Shaposhnikova, 2017). We opt for the "blueprint view," as this is the dominating one in the research. It is also appears to be the view of ALICE (2017), as its roadmap contains a plan with technical milestones for how to implement the PI by 2050.

Our review suggests an array of questions to be addressed in future research. Treiblmaier *et al.* (2016) encourage PI researchers to increasingly build on theory and on a similar note, we stress the importance of a future cumulative approach. Addressing the current challenges of PI's conceptual development listed here would likely provide a solid ground for evaluating actual implementations of PI in terms of its intended effects to solve the grand sustainability challenge.

Note

1. Preliminary sum as of December 28, 2015 according to the Horizon 2020 web pages (https://ec.europa.eu/research/participants/portal/desktop/en/opportunities/h2020/topics/2096-mg-5.4-2017.html).

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(The Appendix follows overleaf.)

Appendix

Table AI.
Publications included in the review of the Physical Internet

Paper	Key construct (s)	Theory applied	Method	Empirical data	Technological blueprints (organizational readiness)	Promised effects of the Physical Internet (external pressure)	Business models (perceived benefits)	Adoption
Montreuil (2011)	TCP/IP as metaphor SC pooling	Technical references	Conceptual	None	Contains the overarching design and characteristics of PI	See Figure 3		The author states a large number of questions to be addressed by many types of organizations as the PI “emerges”
Montreuil, Sarraj, Cimon and Poulin (2012)	Business model innovation	n/a	Conceptual	None			PI makes “ephemeral” and “mash-up” business models profitable Does not describe the value creating and profit generating mechanisms	
Sarraj, Ballot, Pan, Hakimi and Montreuil (2014)	TCP/IP as metaphor SC pooling	Supply chain pooling	Simulation	Data from two French retail chains and 106 common suppliers. 12 weeks of data	Explains the decision process in Pi-hubs	Lower costs and 60% CO_2 reduction based on the simulation model		
Sarraj, Ballot, Pan and	TCP/IP as metaphor	Supply chain pooling	Conceptual Mathematical modeling	None	Detailed explanation of the routing	Mathematical model showing that excluding		

(continued)

Table AI.

Paper	Key construct (s)	Theory applied	Method	Empirical data	Technological blueprints (organizational readiness)	Promised effects of the Physical Internet (external pressure)	Business models (perceived benefits)	Adoption
Montreuil (2014)	Transport network				protocols for the Physical Internet	warehouses in the freight flows increases efficiency		
Rougés and Montreuil (2014)	Crowdsourcing Physical Internet	n/a	Conceptual	None				
Montreuil *et al.* (2013)	Physical Internet Crossdocking	n/a	Conceptual	None	Provides the functional design for a unimodal road-based crossdocking hub			
Ballot *et al.* (2013)	Physical Internet	n/a	Conceptual	None	Provides the functional design for a road-rail hub	Analysis of hub design performance		
Meller *et al.* (2013)	Physical Internet	n/a	Conceptual Mathematical modeling	None	Provides the functional design for a road-based transit center	Analysis of center design performance		
Montreuil, Ballot and Fontane (2012)	TCP/IP as metaphor SC pooling	Technical references	Conceptual	None	A 7-layer model of the Physical Internet, aligned to the Digital Internet			
Furtado *et al.* (2013)	Agent-based modeling Physical Internet	n/a	Simulation (agent based)	None		Strong improvement of fill rates through PI		
Lin *et al.* (2014)	Modular packaging	n/a	Mathematical modeling	Data from US-based retailer		Increasing fill rate from 66.1% to 73.4-79.6% with PI		

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Table AI.

Paper	Key construct (s)	Theory applied	Method	Empirical data	Technological blueprints (organizational readiness)	Promised effects of the Physical Internet (external pressure)	Business models (perceived benefits)	Adoption
Arnäs *et al.* (2013)	Hybrid shipment control Smart goods	Design theory Transport planning	Simulation	Daily freight volumes (for each network relation for a sample of eight weeks	Design theory on hybrid shipment control			
Hakimi *et al.* (2012)	n/a	n/a	Simulation	Weekly flows of products				
Pan *et al.* (2015)	Inventory management SC pooling	Inventory control theory	Simulation	n/a		PI can potentially reduce inventory levels while maintaining the same service level		
Tran-Dang *et al.* (2017)	Intelligent container	Sensor network theory	Simulation Mathematical modeling	None	Arrangement orientation and coordinates of π-containers and their corresponding sensors			
Ballot *et al.* (2012)	SC pooling	n/a	Simulation	Yes	Obtained from simulation	Large sustainability improvements		
Hakimi (2014)	SC pooling	n/a	All	n/a				
Sohrabi and Montreuil (2011)	SC pooling	n/a	Mathematical modeling	None				
Ballot *et al.* (2014)	n/a	n/a	All	Yes				

(*continued*)

Table AI.

Paper	Key construct (s)	Theory applied	Method	Empirical data	Technological blueprints (organizational readiness)	Promised effects of the Physical Internet (external pressure)	Business models (perceived benefits)	Adoption
Pan and Ballot (2015)	Internet of things	n/a	Simulation Mathematical modeling	None				
Le Roch *et al.* (2014)	Pallets Intelligent products	n/a	Experiment (case study)	Yes				
Yang *et al.* (2015)	Inventory management	Inventory control theory	Simulation	None				
Pan, Xu and Ballot (2014)	Transport auction	Auction theory	Simulation	None	Proposal for PI transport auctioning		Internal PI business model	
Othmane *et al.* (2014)	Transport auction Winner determination problem	n/a	Mathematical modeling	None	Including reputation of carrier in auction			
Colin *et al.* (2015)	Routing	n/a	Mathematical modeling	None	Proposal for routing of one ship			
Crainic and Montreuil (2016)	Physical Internet Transport networks City logistics	n/a	Conceptual	None	Design of hyperconnected cities			

(*continued*)

Table AI.

Paper	Key construct (s)	Theory applied	Method	Empirical data	Technological blueprints (organizational readiness)	Promised effects of the Physical Internet (external pressure)	Business models (perceived benefits)	Adoption
Darvish *et al.* (2016)	Distribution network Physical Internet	n/a	Linear programming	Yes		Significantly lower network cost through pooling		
Cimon (2014)	n/a	Principle-agent	Conceptual	None			Discussing potential conflicts	
Landschutzer *et al.* (2015)	π-containers	n/a	Product design	None	1. π-containers blueprint 2. Loading process			
Lin and Cheng (2016)	Internet of things	n/a	Prototype	Case study				
Oktaei *et al.* (2014)	Physical Internet Business model	Canvas business model	Conceptual	None			Business model for a Pi-transit center	
Qiao *et al.* (2016)	Less-than-truckload dynamic pricing (LTLDP) Physical Internet	n/a	Mathematical modeling	None			Pricing model for LTL	
Sallez *et al.* (2016)	“Activeness” Physical Internet	n/a	Simulation	None	Blueprint of activeness of π-containers			

(*continued*)

Table AI.

Paper	Key construct (s)	Theory applied	Method	Empirical data	Technological blueprints (organizational readiness)	Promised effects of the Physical Internet (external pressure)	Business models (perceived benefits)	Adoption
Simmer *et al.* (2017)	Physical Internet	n/a	Semi-structured interviews	16 LSP interviews			Interviews outline challenges with the horizontal collaboration (indirectly PI)	
Venkatadri *et al.* (2016)	Physical Internet SC pooling	n/a	Mathematical modeling	None		Lower inventory cost, shorter leadtimes and comparable transportation costs		
Walha *et al.* (2016)	Physical Internet Railroad hub	n/a	Mathematical modeling Agent-based simulation	None	Grouping algorithm for container allocation			
Yao (2016)	Physical Internet e-Commerce	n/a	Mathematical modeling	None	Algorithm for single shipments			
Zhang *et al.* (2016)	Physical Internet Product service system	n/a	Mathematical modeling	None			PSS business model	
Zhong *et al.* (2016)	Production control	n/a	Case study Prototype design	Single case	Production system supporting PI			

(*continued*)

Table AI.

Paper	Key construct (s)	Theory applied	Method	Empirical data	Technological blueprints (organizational readiness)	Promised effects of the Physical Internet (external pressure)	Business models (perceived benefits)	Adoption
Zhong *et al.* (2017)	Production control	n/a	Case study Prototype design	Single case	Production system supporting PI			
Treiblmaier *et al.* (2016)	Theory	n/a	Literature review	None				
Kong *et al.* (2016)	Auction logistics center	n/a	Mathematical modeling	None	Auction logistics center			
Yang *et al.* (2017a)	Inventory management	n/a	Mathematical modeling	None		PI inventory model outperforms traditional inventory model for demand uncertainties and SC disruptions		
Fazili *et al.* (2017)	n/a	n/a	Mathematical modeling	None		Lower social cost for drivers Hybrid structure		
Mohamed *et al.* (2017)	City logistics	n/a	Mathematical modeling	None	Modeling of PI in urban context			
Yang *et al.* (2017b)	VMI	n/a	Simulation	None		Table II shows an average saving of 77% in total costs with the PI inventory model compared with the classic inventory model ClassicSTEP		