International Journal of Production Research, 2018
https://doi.org/10.1080/00207543.2018.1494392

Towards freight transport system unification: reviewing and combining the advancements in the physical internet and synchromodal transport research

Tomas Ambra[a,b,c*], An Caris[c] and Cathy Macharis[a]

[a]*Research Group MOBI, Vrije Universiteit Brussel, Brussels, Belgium;* [b]*Research Foundation Flanders (FWO), Brussels, Belgium;* [c]*Research Group Logistics, Universiteit Hasselt, Diepenbeek, Belgium*

To achieve socio-economic and environmental sustainability, utilization of existing capacities and assets has become a key challenge for the transportation sector. This challenge has been recognised by many scholars, policy makers and practitioners leading to a substantial body of new concepts and models. The rather parallel evolution of the Physical Internet (PI) and synchromodal transport presents an opportunity to improve the current unsustainable freight transportation, by inducing a positive modal shift from roads to rails and inland waterways, and improving service levels by better connecting production research with freight movement. This paper thus examines the synchromodal and PI state-of-the-art models together with their designs, methodologies and findings proposed in the scientific literature. The main objective is to assess and explore the correlations between these two concepts in order to understand how they can reinforce each other. Despite the integrated vision of the Alliance for Logistics Innovation through Collaboration in Europe, the findings of this paper yield no well-established interconnections in the scientific literature between PI and synchromodality as they both merely coexist in parallel and address different dimensions, scales and levels of abstraction. This paper thus identifies potential synergies, future research directions and critical questions to be considered by modellers, developers and policy makers.

Keywords: synchromodality; intermodality; physical internet; modelling; systematic review; multimodal transport

1. Introduction

With projected growth of international trade and cargo demand, the current infrastructural capacities are put under pressure resulting in congestion problems, safety issues, environmental concerns and decreasing reliability of services. Instruments used in the 'business as usual' approach are not sufficient to cope sustainably with the expanding market (EC 2011) as the freight share of total transport green-house gases is projected to increase from 42% in 2010 to 60% in 2050 which will present a major challenge to decarbonise the freight transport sector (OECD 2015). The ambition of the European Commission is to shift 30% of road freight transport by 2030 to environmentally friendlier modes that have lower societal impact, such as rail and inland waterways (IWW). This shift should reach 50% by 2050. Therefore, it is necessary to introduce innovative solutions that would support optimal integration of different transportation modes and their cost-effective use. To achieve socio-economic and environmental sustainability, utilisation of existing capacities and assets has become a key challenge for the transportation sector. This challenge has been recognised by many scholars, policy makers and practitioners leading to a substantial body of new concepts and which are described in the following sub-sections.

1.1. *Synchromodal transport and existing reviews*

The concept of synchromodal transport/synchromodality is the most recent stage in the conceptual evolution of multimodal transport. Multimodality is understood as a fundamental core term which involves at least two different modes of transportation (UNECE 2009). Other concepts have evolved around this core notion extending it by additional new features. Such an extension is intermodal transport of which the main quality criterion is chain integration with standardised container boxes (SteadieSeifi et al. 2014; Reis 2015). Yet two more terms have emerged; combined and co-modal transport, where the former is introduced by UNECE (2001) and the latter by EC (2006). Both terms are virtually intermodal transport where the main difference is that combined transport applies more emphasis on the usage of road for as short as possible within the initial/final leg, and co-modal on the efficient/optimal utilisation of resources. Given the intermodal nature of these latest concepts, intermodality as such had gained its peak between 2011 and 2013 in terms of publications (Mathisen and Hanssen 2014)

*Corresponding author. Email: tomas.ambra@vub.be

since the field's manifestation in mid-90s (Bontekoning, Macharis, and Trip 2004). As a result of the growing body of literature related to intermodal transport, several scholars have provided reviews of the topic. An extensive early overview of operations research (OR) within the intermodal context was conducted by Macharis and Bontekoning (2004) who assessed the literature in three planning horizons (strategic, tactical and operational) as well as the type of actors involved in the intermodal chain (drayage, terminal, network and intermodal operators). Their work was later on updated by Caris, Macharis, and Janssens (2008). More recently, SteadieSeifi et al. (2014) devoted their work to multimodal transport research covering the time period from 2005 until 2013 in which they built on the previous work of Bektas and Crainic (2007) and Christiansen et al. (2007).

The synchromodal term was coined in 2010 by Dutch scholars Tavasszy, van der Lugt, and Hagdom (2010). It presents an extension of intermodal transport by including real-time re-routing of loading units over the network to cope with disturbances and operational or customer requirements (Verweij 2011). Unexpected data changes caused by disturbances or other events result in congestion, delays and time/money losses. The synchromodal concept has a potential to offer better performance than intermodal transport on flexibility, reliability and other modal choice criteria. The incorporation of real-time and dynamic elements can facilitate re-routing, re-scheduling and modal shift, contributing to higher competitiveness (Ghiani et al. 2003). The main system changes to enable synchromodality are related to (i) transactions allowing for a-modal booking, (ii) governance arrangements resulting in better operational alignment of different modes, (iii) institutions creating standardised cooperative schemes and (iv) cultural mind-shift moving from 'predict and prepare' to 'sense and respond' (Tavasszy and Konings 2015). In the synchromodal setting, decisions related to modal choice and route are not predefined long in advance, but are taken as late as possible based on real-time infrastructural and operational developments (Verweij 2011). This means the planning and execution horizons are becoming closely interconnected. Synchromodality can be thus perceived as real-time, dynamic and optimised intermodal transport.

1.2. *Physical internet (PI) and existing reviews*

The Physical Internet, mostly referred to as PI or π, is to offer a new fundamental solution to unsustainable operations of production and freight transport to reduce earlier mentioned societal, environmental and economic sustainability; it has been addressed as the global logistics sustainability challenge (Montreuil 2011). 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 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. In other words, the idea resembles an email-sending process where the sender is not concerned about how and by whose network the message is brought to the final destination. The first formal definition of the PI was introduced by Montreuil, Meller, and Ballot (2013) who describe it as an open global logistics system founded on the physical, digital and operational interconnectivity through encapsulation, interfaces and protocols. It has been introduced as a solution to improve the way physical objects are moved, stored, realised, used and supplied throughout the world in order to achieve more economic, environmental and social efficiency. The physical elements that make the PI are π-nodes, π-movers and π-containers (Montreuil, Meller, and Ballot 2010). These physical elements rest on the following main foundation described by Montreuil, Meller, and Ballot (2013), being universal interconnectivity, encapsulation, standard smart interfaces, standard coordination protocols, a logistics web enabler and an open logistics system. Recently, a concept of 'hyperconnected' city logistics has emerged in the work of Crainic and Montreuil (2016) who conceptualise the last segment of the PI logistics and transport networks. Given the rather new concept of PI, there is a limited number of reviews (compared to the previous section) where Sternberg and Norrman (2017) present the first critical review of the concept and Pan et al. (2017) who provide a very brief overview of the current PI research.

1.3. *Problem statement and paper positioning*

Since their manifestation, synchromodal transport and PI have received significant attention from researchers but also from policy makers. The latter concerns promoting these two concepts by the European Technology Platform called Alliance for Logistics Innovation through collaboration in Europe (ETP-ALICE). The ALICE platform is to set a comprehensive research strategy as well as innovation and market deployment of supply chain management and logistics in Europe, and to advise the European Commission on the EU Horizon2020 program implementation (ALICE 2017).

According to the roadmap set by the platform, the PI is to be fully implemented by 2030 after reaching specific intermediate goals (Figure 1). Our work offers a more profound understanding of the current state of the research field and its advancements towards the integrated visions of ALICE with regard to synchromodality and PI.

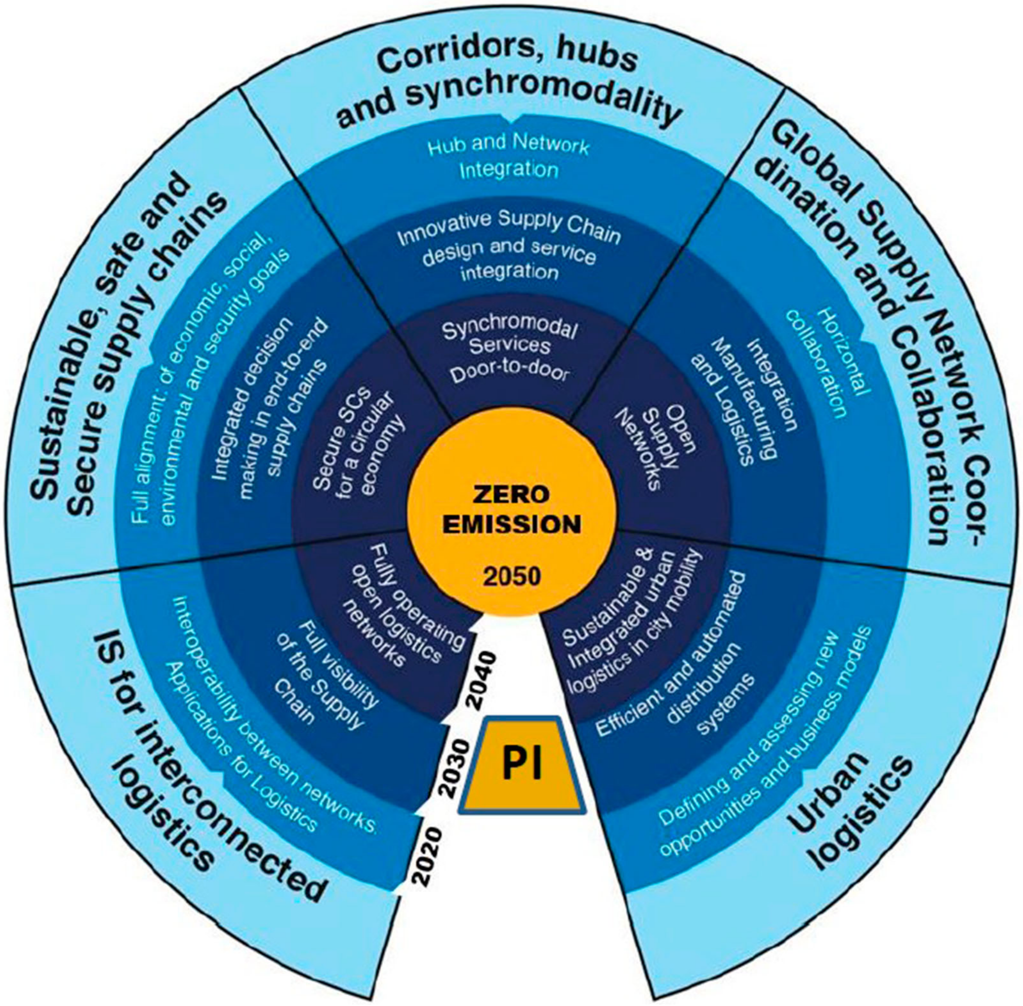

Figure 1. ALICE roadmap towards zero emissions (renewed version). Source: ALICE (2017).

The main contributions of this paper are the exposure and identification of scientific practices related to the two concepts. We pose the following research question: Are the current synchromodal and PI research streams well intertwined in order to meet the visions and goals set by ALICE and the European Commission? This work should be perceived as a compressed overview of the most recent developments, and is useful for scholars, modellers and decision makers to identify new opportunities for combining these two concepts in their models, research and policy objectives. The review scarcity of these two concepts, let alone their combination, confronts the academic sphere with unexplored structures and linkages that may alter the way freight transport is modelled and realised.

The remainder of the paper includes some parts from a conference paper (Ambra et al. 2017) and is structured as follows. Section 2 depicts the applied search strategy. Section 3 provides a descriptive overview of the selected synchromodal and PI-related literature. The gaps and correlations are explored and assessed in section 4; to the best of our knowledge, such synergies have not been addressed in any previous reviewing works and this paper is to fill this gap. Besides discussing the dimensions and research focuses in section 4, we provide a more general discussion and potential future research directions as well as critical questions in section 5. We then conclude our work in section 7.

2. Methodology

We followed the systematic literature review guidelines proposed by Durach, Kembro, and Wieland (2017) which consist of 6 steps. Step 1 refers to defining the research question and focus of our analysis; this step is presented in the introduction. Secondly, we defined our exclusion criteria; documentation and reports that are not in English were excluded. We mainly aimed at journal and conference papers that concern the physical internet and/or synchromodal transport. The primary studies had to contain research outcomes or analyses which is why we ignored project descriptions that still need to carry out actual research. Master theses and other projects not presented internationally were excluded from our scope of search.

We applied a computerised search strategy to detect and gather papers from different channels which appeared between 2010 and 2017 in order to acquire a broader baseline sample. The electronic databases used for the search were Google scholar, research gate, Social science research network database and web of science. Relevant research retrieved from authors we knew about based on informal connections is also included in this review together with studies tracked through previous citations of earlier work (ancestry approach). Based on this search, 2 synchromodal publications were added despite being published before 2010 (Ziliaskopoulos and Wardell 2000; Chang, Floros, and Ziliaskopoulos 2007).

When conducting the electronic database search, search strings such as 'physical internet' and 'synchromodal transport' were used for each concept, respectively. These words of interest had to appear in the title, abstract or keyword section of the publications. The former, physical internet, yielded many (irrelevant) results such as 'internet-based physical activities related to diabetes' to name one. We thus inserted additional strings 'logistics' and 'freight' to narrow down the search output. Afterwards, the selected publications were triangulated with Sternberg and Norrman (2017) and Pan et al. (2017). However, some documents that are referred to in Pan et al. (2017) were not retrievable; only citations were available without the paper itself; these publications are thus excluded as the content could not be verified. Lastly, extended abstracts were filtered out. As for the latter, synchromodal transport, only freight-related research was considered whereas other fields, such as education and 'synchromodal learning classes' were filtered out. This was done be adding an extra set of strings such as 'synchromodality', 'dynamic' and 'flexible freight transport' to narrow down the scope. Several conference papers have become journal publication; these duplicates were removed and substituted by the corresponding journal papers.

In total, our search strategy resulted in 114 publications among which, 57 were synchromodal papers (34 conference papers + 23 journal papers) and 57 physical internet papers (27 conference papers and 30 journal papers). Even though conference papers do get peer-reviewed, the peer-review process is not as thorough as journal paper peer-revisions. Therefore, we decided to account for quality assured work and confine our review to journal papers only.

In this regard, Figure 2 depicts the number of journal papers published between 2010 and 2017. It can be inferred the journal publications of both concepts have a steep increasing trend from 2014 onward. This is a testament to the fact that both concepts have gained more interest in academia and this trend should increase even further, given the amount of conference papers which may transform into journal publications. The literature review presented herein considers 53 journal papers that are used for our analysis in the following sections. An overview of synchromodal and PI publications is provided in section 3.

3. Descriptive overview

3.1. *Synchromodality papers*

The journal papers that met our search criteria for synchromodal transport, described earlier in the methodology, are presented in Table 1. It is divided into 5 columns where the focus is given on (1) the targeted actor(s) of the authors' paper, (2) the main objective value that the paper seeks to improve/optimise or, in case the author does not apply a modelling approach, the general goal of the paper, (3) the method used in order to determine whether the paper is based on analytical/mathematical modeling, simulation modelling or qualitative analyses. Furthermore, (4) the paper's title is provided as it captures the main essence of the work and (5) the confinement which determines the spatial dimension of the work; this dimension refers to closed 4-wall environments such as hubs, warehouses, factories or DCs with a low level of

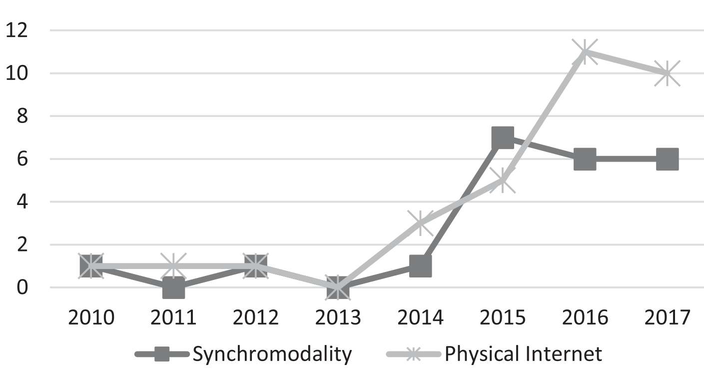

Figure 2. Evolution of Synchromodal transport (synchromodality) and physical internet journal publications from 2010 onward.

Table 1. Overview of synchromodal papers and their elements. LSPs in the table are third party logistics service providers who possesses own resources and provide a complete shipment service.

Reference	Targeted actor (s)	Objective value/ goal	General method	Title	Confinement/focus
Ziliaskopoulos and Wardell (2000)	Network operators	Transfer time reduction	Analytical modeling	An intermodal optimum path algorithm for multimodal networks with dynamic arc travel times and switching delays	Interregional intermodal network
Chang, Floros, and Ziliaskopoulos (2007)	LSPs	Transfer cost reduction	Analytical modeling	An Intermodal Time-Dependent Minimum Cost Path Algorithm	Intermodal rail corridor
Bock (2010)	LSPs	Minimise cost of disturbance	Analytical modeling	Real-time control of freight forwarder transportation networks by integrating multimodal transport chains	Intermodal rail corridor
Pleszko (2012)	-	-	Survey/ questionnaire	Multi-variant configurations of supply chains in the context of synchromodal transport	-
SteadieSeifi et al. (2014)	Researchers	Provide overview of planning horizons	Review	Multimodal freight transportation planning: A literature review	Evolution of multimodal planning problems
Harris, Wang, and Wang (2015)	Researchers	Identify ICT trends in multimodal transport	Review	ICT in multimodal transport and technological trends	ICT technologies in Europe
Reis (2015)	Researchers	Unified ontology	Review	Should we keep on renaming a + 35-year-old baby?	Synchromodal concept evolution
Li, Negenborn, and De Schutter (2015)	LSPs, terminal operators	Modal split, delivery cost	Analytical modeling	Intermodal freight transport planning – A receding horizon control approach	Interregional intermodal network
van Riessen, Dekker, and Lodewijks (2015a)	LSPs, terminal operators	Reduce weekly transport cost	Analytical modeling	Service network design for an intermodal container network with flexible transit times and the possibility of using sub-contracted transport	Interregional intermodal network
Xu et al. (2015)	Container carrier	Profit gain via container capacity allocation	Analytical modeling	Model and algorithm for container allocation problem with random freight demands in synchromodal transportation	Interregional intermodal network
Nabais, Benítez, and Botto (2015)	LSPs, terminal operators	Cargo peaks identification, modal split	Analytical modelling	Achieving transport modal split targets at intermodal freight hubs using a model predictive approach	Interregional intermodal network
van Riessen, Lodewijks, and Dekker (2015b)	Network operators	Impact and relevance of disturbances	Analytical modeling	Impact and relevance of transit disturbances on planning in intermodal container networks using disturbance cost analysis	Interregional intermodal network
Van Der Vorst et al. (2016)	Shippers	Report on synchromodal case studies	Report	Towards Collaborative Responsive Logistics Networks in Floriculture	Interregional intermodal network
Behdani et al. (2016)	LSPs	Waiting time / cost reduction	Analytical modeling	Multimodal Schedule Design for Synchromodal Freight Transport Systems	Interregional intermodal network
Mes and Iacob (2016)	LSPs/ forwarders	Time, cost and CO_2 reduction	Analytical modeling	Synchromodal Transport Planning at a LSPs	Intermodal rail corridor
Dobrkovic et al. (2016)	LSPs	Vessel trajectory predictions	Systematic review	Towards an approach for long term AIS-based prediction of vessel arrival times	IWWs

(*Continued*)

Table 1. Continued.

Reference	Targeted actor (s)	Objective value/ goal	General method	Title	Confinement/focus
Zhang and Pel (2016)	Government	System cost, time, CO_2, modal split	Simulation modelling	Synchromodal hinterland freight transport: Model study for the port of Rotterdam	Interregional intermodal network
Bendul and Erfurth (2017)	LSPs	Transport time and reliability	Analytical/ computational modelling	Transportation time and reliability in intermodal transport chains	Intermodal rail corridor
Dong et al. (2017)	LSPs/ Shippers	Modal shift to rail	Analytical modelling	Investigating synchromodality from a supply chain perspective	Intermodal rail corridor
Li, Negenborn, and De Schutter (2017)	LSPs	Minimise container delivery cost	Analytical modelling	Distributed model predictive control for cooperative synchromodal freight transport	Interregional intermodal network
Perboli et al. (2017)	LSPs	Cost and emission reduction	Survey/ questionnaire	Synchro-modality and slow steaming	Interregional intermodal network
van Riessen and Dekker (2017)	LSPs	Increase revenue/ capacity utilisation	Analytical modelling	The Cargo Fare Class Mix problem for an intermodal corridor	Interregional intermodal network

abstraction. These confinements can be also higher structures with a higher level of abstraction and more open environments (outside of the four-walls) such as a city or states that contain road, rail and IWW infrastructures that connect the earlier mentioned hubs.

One of the early models concerning dynamic elements in a multi-modal transport network is proposed by Ziliaskopoulos and Wardell (2000). The authors developed an intermodal time-dependent algorithm which accounts for delays at mode and arc switching points. This work has been extended by Chang, Floros, and Ziliaskopoulos (2007) with more emphasis on intermodal minimum costs rather than time. More recently, Bock (2010) proposed an update handling real-time approach in a dynamic context to support freight forwarders' decision-making. The model considers activities executed by partners, hubs or forwarders' own fleet and accounts for vehicle breakdowns, route blockages and traffic congestion scenarios. Pleszko (2012) descriptively reports on the share of modes in intermodal transport and quality preferences of companies.

Harris, Wang, and Wang (2015) evaluate current Information and Communication technology (ICT) developments in multimodal transport based on 33 EU projects. Their findings indicate that 23 of the projects make use of wireless/ mobile technologies and the internet of things (IoT), whereas cloud computing and social network (Web 3.0) are used by 3 and 2 projects, respectively. van Riessen, Dekker, and Lodewijks (2015a) investigate the cost-impact of using intermediate transfers within the European Gateway Services (EGS) network design. The proposed mathematical model considers self-operated and sub-contracted services with penalised overdue deliveries to allow flexibility and mode switching. In van Riessen, Lodewijks, and Dekker (2015b) a Linear Container Allocation model with time restrictions is developed which is used for evaluating the influence of disturbances such as early/late service departures and cancellation of inland services. The model was also tested within the EGS network. As far as predictability is concerned, Nabais, Benítez, and Botto (2015) apply a Model Predictive Control in a cooperative framework between transport providers and intermodal hubs. The authors' application is to anticipate cargo peaks at intermodal terminals with an objective to push the cargo closer towards its final destination. Li, Negenborn, and De Schutter (2015) apply a receding horizon approach to intermodal freight transport planning problems among deep-sea terminals and intermodal terminals to address dynamic behaviours of transport demand, traffic conditions and also to determine the intermodal route and container assignment at the same time. Xu et al. (2015) assess the container carrier perspective with a focus on container allocation problem with random freight demands. The problem is formulated as a stochastic integer programming model with an objective to allocate container capacity in order to maximise total transportation profit in a synchromodal transportation network including rail, IWW and road modes.

Behdani et al. (2016) present a mathematical model for designing integrated service schedules for synchromodal freight transport systems. The benefits of the integrated design are compared to a base case with separate planned transport services without any coordination between barges and trains. Another perspective is evaluated by Mes and Iacob (2016) who propose a synchromodal planning algorithm used within an LSP's control tower. Their case study demonstrates a reduction in cost and CO2 as most of the orders could make a modal shift mainly from road to rail to destinations such as Italy, Switzerland and Austria. Varying results are observed in Zhang et al. (2016) who developed a comparative analysis model of intermodal and synchromodal transport taking into account economic, societal and environmental aspects. The results of this study yield no significant economic benefits due to the short distance and higher transfer/transshipment costs, but they do also lead to a positive modal shift and lower CO_2 emissions. Van Der Vorst et al. (2016) report on the logistics concepts in the floriculture industry where they synchromodal metro model contributed to cost reduction. Dobrkovic et al. (2016) review algorithms for maritime route predictions using Automatic Information System (AIS) data who found that current approaches focus mainly on anomaly detection and vessel collision avoidance, and not on vessel arrival estimation (ETA) which would be of interest to LSPs to improve their planning and manage disturbances.

Revenue management is also an important aspect of synchromodal transport; van Riessen and Dekker (2017) introduce the Cargo Fare Class Mix problem to demonstrate that booking limits for differentiated fare classes at tactical level lead to increased revenue. Li, Negenborn, and De Schutter (2017) use 3 distributed model predictive flow control approaches in the context of cooperative synchromodal transport planning among hinterland entities such as deep-sea ports and inland terminals. Dong et al. (2017) take a different perspective and assess synchromodality from a more holistic supply chain perspective. The authors demonstrate that including inventory management into modal options can increase the modal share of rail and decrease cost as well as emissions. Bendul and Erfurth (2017) investigate the effect of long-haul rail transport on transportation time and its reliability. Despite omitting crucial elements such as capacity constraints and handling times, their work illustrates that time reliability decreases with increased distance in long-haul transport. Perboli et al. (2017) provide a preliminary qualitative analysis of the Horizon2020 SYNCHRO-NET project from a managerial perspective. The authors focus on stakeholders' preferences within their project. The stakeholders consist of logistics operators, shippers, public and port authorities.

3.2. *Physical internet papers*

Similar to the previous section, the journal papers that met our search criteria for physical internet, described earlier in the methodology, are presented in Table 2. Given the main objective of this paper, which is to unify the synchromodal and PI concepts, this section provides a description of the PI, its foundations and elements.

Lin et al. (2014) devise a model for selecting standard modular containers (boxes) for a set of products. The authors minimise unused capacity by calculating container dimensions, product assignment and their quantity. Empirical test results indicate reduction in the container number per shipments at the expense of a slight increase on shipping volume per item. The π-modular containers are meant to facilitate interconnection in open PI networks to avoid dedicated, fragmented and overlapping supply flows; Sarraj et al. (2014) numerically demonstrate the potential of merging container flows by interconnecting logistics networks and protocols. The results indicate a significant CO_2 reduction and an increase in weight fill rate contributing to lower costs.

An explicit research on π-containers has been carried out by Landschützer, Ehrentraut, and Jodin (2015) who describe a first engineering process for developing modular and multifunctional load units within the fast-moving consumer goods industry. The findings of the project show the box utilisation depends strongly on the number of used box sizes leading to a 22.5% decrease in required trailers and 81% of item utilisation of the unit load when the number of boxes is higher. Pan and Ballot (2015) demonstrate the benefits of knowing asset positions via a framework to optimise the repositioning open container tracing based on radio frequency identifiers (RFID). Their simulation results show a decrease in inventory levels at the expense of slightly higher travelled kilometres per container rotation. Pan et al. (2015) provide and exploratory simulation study of inventory control models in PI. The study indicates increasing total savings with higher retailer density in the PI network where several replenishment paths are interconnected. Qiu et al. (2015) propose a new business model based on and IoT-enabled infrastructure. Their exploratory work is to create real-time visibility and information sharing to identify available capacities and assets.

Darvish, Larrain, and Coelho (2016) link the vehicle routing problem with lot-sizing problem in order to address a more holistic production-routing problem. Their case study, focused on resource sharing, leads to storage and transport cost savings. One of the first pricing models in the PI context is investigated by Qiao, Pan, and Ballot (2016) to facilitate carriers' decision making with regard to price propositions in a dynamic bidding environment for less-than-truckloads. The study considers parameters such as cost, capacity and demand, and tests unique and variable price strategies. Hofman et al. (2016) present semantic technology as an enabler for adaptive synchromodal planning by improving visibility and thus predictability of turnaround times at container terminals. This paper is the first and last to mention synchromodal transport and the PI notion. However, the direct link is not apparent. The PI process visibility has also emerged in several different industry applications such as the solar cell industry (Lin and Cheng 2016).

As far as the inner π-hub operations are concerned, Kong et al. (2016) transform the auction business into a new paradigm in combination with the PI. It offers a shift from a classical approach, which relies mainly on human experience, to a PI approach contributing to real-time visibility and tractability of auction processes and products. Walha et al. (2016) study the rail-road π-hub allocation problem where the π-hub is distinguished from a classical road-rail terminal by having

Table 2. Overview of physical internet papers and their elements.

Reference new	Targeted actor(s)	Objective value/goal	General method	Title	Confinement/ focus
Montreuil, Meller, and Ballot (2010)	Researchers, terminals and warehouses	Introduce building blocks of PI	Conceptual overview/ report	Towards a Physical Internet: the impact on logistics facilities and material handling systems design and innovation	Terminals and warehouses
Montreuil (2011)	Shippers, LSPs, warehouses, researchers	Introduce PI vision	Conceptual overview/ report	Toward a Physical Internet: meeting the global logistics sustainability grand challenge	Overall supply chain
Montreuil et al. (2012)	Shippers, LSPs, warehouses, researchers	Connect business models to PI	Conceptual overview/ report	The physical internet and business model innovation	Overall supply chain
Lin et al. (2014)	Shippers	Maximise packaging container space utilisation	Analytical modelling	A decomposition-based approach for the selection of standardised modular containers	Factor, warehouse
Sarraj et al. (2014)	Shippers, LSPs, warehouses	Increase assert utilisation, decrease distance and travel flows	Analytical modelling	Analogies between Internet network and logistics service networks: challenges involved in the interconnection	Interregional road network, warehouse
Landschützer, Ehrentraut, and Jodin (2015)	Warehouses, carriers	Handling cost, volume utilisation	Simulation modelling	Containers for the Physical Internet: requirements and engineering design related to FMCG logistics	Box
Pan and Ballot (2015)	Shippers, LSPs, warehouses	Minimise inventory level and transport distance	Simulation modelling	Open tracing container repositioning simulation optimisation: a case study of FMCG supply chain	Interregional road network, warehouse
Pan et al. (2015)	Shippers	Reduce transport and inventory costs	Simulation modelling	Perspectives of inventory control models in the Physical Internet: A simulation study	Interregional road network, warehouse
Qiu et al. (2015)	LSPs, warehouses, shippers	Create transparency for real-time asset sharing	Review	Physical assets and service sharing for IoT-enabled Supply Hub in Industrial Park	Interregional road network, warehouse
Darvish, Larrain, and Coelho (2016)	LSPs, warehouses, shippers	Minimise production inventory and delivery costs	Analytical modelling	A dynamic multi-plant lot-sizing and distribution problem	Warehouse, interregional road network
Hofman et al. (2016)	-	-	Semantic modelling	Semantic technology for enabling logistics innovations–towards Intelligent Cargo in the Physical Internet	Interregional intermodal network
Kong et al. (2016)	Shippers, warehouses	Logistics cost, labour cost,	Analytical modelling	Scheduling at an auction logistics centre with physical internet	Warehouse
Lin and Cheng (2016)	Shippers, warehouse	Lower labour cost, higher production capacity	Pilot experiment	Case study of physical internet for improving efficiency in solar cell industry	Warehouse
Maslarić, Nikoličić, and Mirčetić (2016)	Researchers	Identify PI challenges in industry 4.0	Review	Logistics response to the industry 4.0: the physical internet	Overall supply chain
Qiao, Pan, and Ballot (2016)	Carriers	Maximise revenue when bidding	Analytical modelling	Dynamic pricing model for less-than-truckload carriers in the Physical Internet	Interregional road network, warehouse

(*Continued*)

Table 2. Continued.

Reference new	Targeted actor(s)	Objective value/goal	General method	Title	Confinement/ focus
Sallez et al. (2016)	Terminals	Container evacuation time	Simulation modelling	On the activeness of intelligent Physical Internet containers	Rail terminal
Venkatadri, Krishna, and Ülkü (2016)	Carriers	Minimise handling and delivery cost	Analytical modelling	On Physical Internet logistics: modeling the impact of consolidation on transportation and inventory costs	Interregional road network
Walha et al. (2016)	Terminals	Minimise container travel distance to dock	Simulation modelling	A rail-road PI-hub allocation problem: Active and reactive approaches	Terminal
Yao (2016)	Shippers, LSPs	Delivery cost, load rate	Analytical modelling	Optimisation of one-stop delivery scheduling in online shopping based on the physical Internet	Interregional road network
Zhang et al. (2016)	LSPs, warehouse operators	Increase container fill rate	Analytical modelling	Smart box-enabled product–service system for cloud logistics	City
Zhong, Xu, and Lu (2016)	Manufacturers, warehouse operators	Reduce paperwork, enhance information flow	Pilot experiment	Physical Internet-enabled manufacturing execution system for intelligent workshop production	Factory
Fazili et al. (2017)	Carriers	Reduce cost and driving time	Simulation modelling	Physical Internet, conventional and hybrid logistic systems	Interregional road network
Mohamed et al. (2017)	LSPs, carriers	Capacity utilisation, vehicle efficiency	Analytical modelling	Modelling and solution approaches for the interconnected city logistics	City
Simmer et al. (2017)	LSPs	-	Interviews	From horizontal collaboration to the Physical Internet–a case study from Austria (Simmer et al. 2017)	-
Tran-Dang, Krommenacker, and Charpentier (2017)	Warehouse operators	Facilitate PI encapsulation process	Analytical modelling	Containers monitoring through the Physical Internet: a spatial 3D model based on wireless sensor networks	Warehouse
Yang, Pan, and Ballot (2017a)	LSPs, warehouses	Introduce PI disruption mitigation strategies	Simulation modelling	Mitigating supply chain disruptions through interconnected logistics services in the Physical Internet	Interregional road network, warehouse
Yang, Pan, and Ballot (2017b)	Shippers, warehouses	Minimise inventory levels, total cost and distances	Simulation modelling	Innovative vendor-managed inventory strategy exploiting interconnected logistics services in the Physical Internet	Interregional road network, warehouse
Zijm and Klumpp (2017)	Researchers	Identify logistics trends and developments	Review	Future Logistics: What to expect, how to adapt	Overall supply chain
Chen et al. (2017)	Carriers	Transport cost reduction	Simulation modelling	Using taxis to collect citywide E-commerce reverse flows: a crowdsourcing solution	City

modular and standard π-containers for freight and by using conveyors, robots or stackers rather than having to deal with all kind of freight (boxes, pallets …) moved by gantry cranes. Last but not least, Yao (2016) applies the shared and open PI logistics network in the context of optimising one-stop delivery scheduling in online shopping. The traditional manufacturer-wholesaler-retailer-customer setting is altered by proposing a manufacturer–customer chain where the commodity packing process is transferred from the retailer to the manufacturer. The results show lower no-load rate, delivery risk and distribution costs at the expense of on-time delivery time windows. Venkatadri, Krishna, and Ülkü (2016) assess the PI from a shipment consolidation perspective by analysing traditional distribution and consolidated distribution within a European city network. The latter case, where the flows are firstly aggregated, demonstrates a reduction in transports and inventory costs. Zhang et al. (2016) create a new product service system based on a smart box and propose a real-time optimisation via a cloud computing platform. Their case study leads to reduction of empty container spaces and total freight distribution. Zhong, Xu, and Lu (2016) introduce manufacturing executive system that makes use of RFID for real-time data collection. The output of the pilot study is qualitatively evaluated, leading to positive staff feedback regarding reduced paper work and increased information reliability.

Mohamed et al. (2017) study the urban transportation problem in a PI-enabled setting by using different types of vehicles. The results show that PI interconnectivity and extra hubs improve transport planning in terms of routing efficiency and reduced postponed demands. Fazili et al. (2017) quantify the benefits and performance of PI compared to a conventional logistics system. The authors found that PI may reduce truck driving distances and decrease emissions at the expense of having more container transfers which make the system reliant on the loading and unloading efficiency of the PI transit centres. In this regard, Tran-Dang, Krommenacker, and Charpentier (2017) propose a solution that has the ability to facilitate container encapsulation by detecting errors and providing updates. These updates related to ‘smart’ containers equipped with wireless sensor nodes which are useful for determining node relationships in their neighbourhood. Sallez et al. (2016) consider the term ‘active’ as it is more expressive than ‘smart’. The authors focus on the (pro)activeness and information exchange among containers where different grouping strategies within a rail terminal are tested. Chen et al. (2017) make use of the extra loading capacity of taxis to collect returned goods in a city. Even though the solution yielded more distances as well as higher lead-times for the return flows when compared to an ideal case, the authors point out positive aspects of such an application such as environmental impact reduction and extra revenue generated for taxi drivers. Yang, Pan, and Ballot (2017a) study the impact of disruptions on hubs and factory plants and assess inventory model resilience within a PI environment of interconnected logistics services. Their simulation results demonstrate that logistics interconnectivity substantially helps to cope with disruptions in terms of penalty, transportation and total costs. Yang, Pan, and Ballot (2017b) build on the work of Pan et al. (2015) by introducing a PI-based inventory optimisation control model. The authors propose a vendor-managed inventory strategy where facilities and transport means are shared based on user demands. The proposed approach illustrates more sourcing and storage options enabled by higher network configuration flexibility. Simmer et al. (2017) qualitatively analyse the needs of logistics service providers (LSPs) from a horizontal collaboration perspective, and conclude with the need for sharable IT structures and lacking necessary trust among the providers.

4. Unifying synchromodal transport and PI

The commonalities of the studied concepts are very noticeable since both constitute of three main pillars with similar characteristics. Figure 3 depicts these synchromodal and PI pillars. Despite the similarities, each element addresses problems at different levels with unequal dimensions. We have divided these dimensions into four levels based on the reviewed papers. The smallest circle represents higher level of detail and corresponds to box engineering designs that focus on exactness of measurements, and abstract less elements from reality. The next circle ‘production and logistics’ has a higher dimensional scale and depicts four-wall environments such as DCs, warehouses or factories. ‘City and urban distribution’ cover higher geographical regions that go beyond four-wall dimensions. The largest dimension corresponds to ‘Corridors and terminals’ which has the largest geographical scale such as interregional and international coverage. Judging by the placement of the blue (synchromodal) and green (PI) circles, it can be inferred that synchromodal transport literature tends to address the higher dimensions where containers are routed at an interregional level, whereas PI authors confine themselves to lower scales by addressing manufacturing processes and mostly road distribution within cities. Nevertheless, these diverging research orientations present opportunities where the concepts can complement each other to create a more resilient and efficient transport system. The following sub-sections elaborate further on these opportunities by assessing the relations between the TEU and π-containers (Order/Demand), moving resources and π-movers (LSP Assets), closing with stationary resources and π-nodes (Freight Grid).

4.1. *TEU and π-containers (Orders)*

The routing of π-containers by π-movers occurs through π-nodes which are the points where the smallest packing containers (p-containers), pallets (h-containers) and larges containers (*t*-containers) enter the PI (π-gateway), are sorted (π-sorters), composed and snapped together (π-composers), stored at specialised PI warehouses (π-storage) and switched or transferred between transport modes at hubs (π-hubs). The observed pattern in the studied literature reveals a tendency towards the

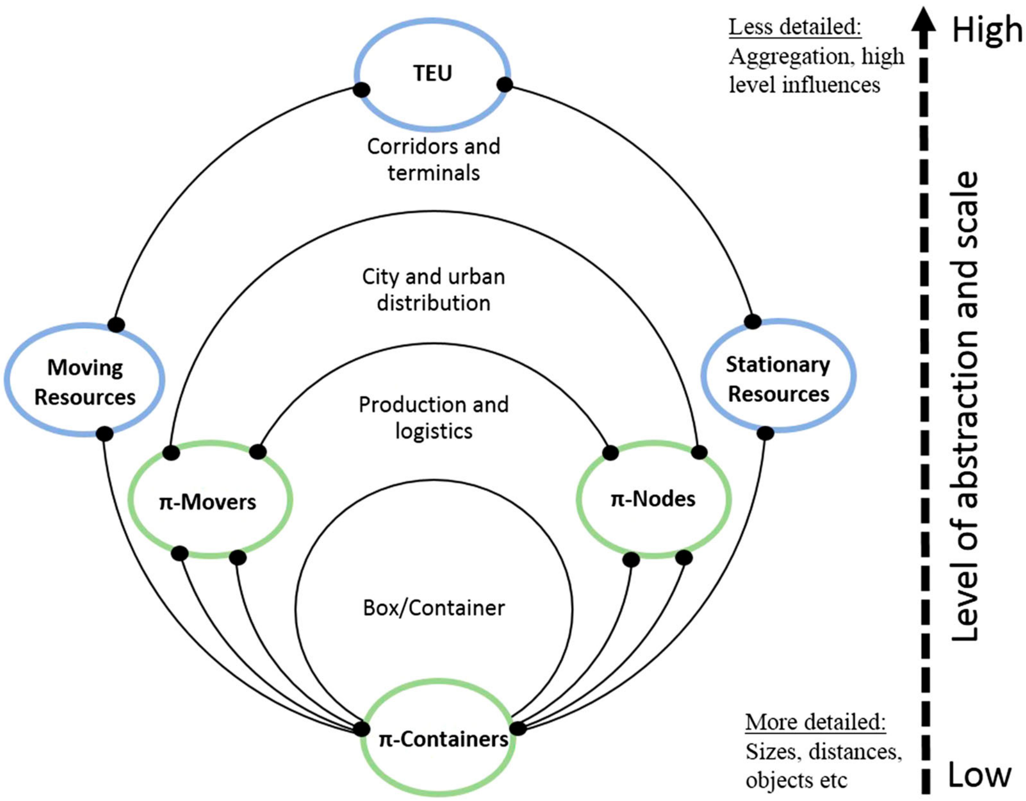

Figure 3. Overlaid research dimensions of the reviewed papers. Green circles represent PI and blue synchromodality.

design and activeness of the π-containers with an emphasis on data sharing connectivity structures and visibility improvements, mainly taking into account the p- and h-container dimensions. Noticeable elements are the container dimension and its overall role. For instance, the largest t-containers are never studied in the PI literature, but form the fundamental basis of synchromodal transport. These are well-established intermodal loading units that are referred to as twenty-foot equivalent units (TEUs) and are globally standardised to facilitate handling and stacking at ports and terminals. The synchromodal container assignment to modes and routes between ports and terminals (Li, Negenborn, and De Schutter 2015), mode-free booking simulations (Zhang and Pel 2016) and stakeholders' preferences regarding lead-times cost and emissions (Perboli et al. 2017) can facilitate t-container research in the PI sphere. On the other hand, synchromodal transport tends to move a lot of 'air' and repositioning of empty containers (empties) presents a challenge. To increase the fill rate of higher level TEUs, the transparency and efficiency at lower levels (p- and h- containers) need to be included via modularisation (Lin et al. 2014), multifunctional load units (Landschützer, Ehrentraut, and Jodin 2015) and advanced encapsulation processes (Tran-Dang, Krommenacker, and Charpentier 2017). The activeness of π-containers results in better grouping strategies (Sallez et al. 2016) and real-time optimisation to decrease empty containers via cloud-computing (Zhang et al. 2016) which can significantly increase capacity utilisation and revenue. In this regard, revenue management of TEUs (van Riessen and Dekker 2017) and the overall container supply chain perspective (Dong et al. 2017) should be intertwined with new bidding models (Qiao, Pan, and Ballot 2016) and auctioning paradigms (Kong et al. 2016) at lower container dimensions to aggregate the benefits. In general, smart tags and sensors described in the reviewed papers, contribute to better visibility of orders based on tracking and location intelligence of the goods encapsulated in the π-containers. The visibility is a crucial factor for establishing a unified system which can then identify dedicated overlapping flows. The unified system should, therefore, be a system that assesses these inefficient flows and translates them into a transparent web where orders and freight volumes can be efficiently bundled at all 3 dimensions being boxes, pallets and containers (TEUs).

4.2. *Moving resources and π-movers (LSP assets)*

In the synchromodal context, moving resources represent barges, trains and trucks that roam between points such as ports and terminals. Tugs, cranes, reach stackers, etc. are also moving resources operating within terminals and ports. The PI concept sees these as movers and their scope and use vary compared to the synchromodal literature. Synchromodality emphasises time and cost depended algorithms that account for delays at mode switching points (Ziliaskopoulos and Wardell 2000; Chang, Floros, and Ziliaskopoulos 2007) and dynamic handling for disruption management (Bock 2010). However, these early real-time dynamic approaches, which are not labelled as synchromodal transport, are rather theoretical and based on abstract analytical/mathematical formulations. In fact, almost all publications take such an approach as can be observed in Table 1. The PI offers greater detail with tracking technologies to determine asset positions via simulation modelling (Pan and Ballot 2015). Therefore, PI studies that concern transparency and real-time sensor structures, may be a better fit as simulation modeling does not ignore the crucial time component that is necessary for visibility, tracking and dynamic reconfiguration during execution runs. As a matter of fact, 9 PI papers make use of simulation modelling (Table 2) compared to 1 synchromodal paper. This also indicates 2 different modelling approaches per concept.

Similar to previously discussed containers, moving assets also vary from a different perspective in terms of modes and geographical scales they cover; while synchromodal studies focus mostly on integration of barge and train schedules, container allocations (Xu et al. 2015; Behdani et al. 2016) and their responsiveness to delays and subsequent cost impact (van Riessen, Dekker, and Lodewijks 2015a,b) that cover longer hauls such as interregional European scales (Mes and Iacob 2016; Bendul and Erfurth 2017), the PI studies take into account mainly the road mode and neglect IWW and rails. The road-only distribution (Venkatadri, Krishna, and Ülkü 2016; Fazili et al. 2017) is often linked to storage and inventory (Darvish, Larrain, and Coelho 2016). Therefore, the main European corridors and hubs are not exploited as the previous three authors consider interregional road flows and other authors such as Mohamed et al. (2017) and Chen et al. (2017) narrow down the scope of moving resources to cities. This is not a problem in itself, but the divergent geographical scopes should be merged to create a more accurate door-to-door services by connecting synchromodal European interregional studies to PI studies which have mostly a local character. As a matter of fact, the physical internet research should make use of the existing synchromodal studies as IWW and rail modes are imperative in attracting and shifting freight flows from road, as depicted by the European Commission targets in our introduction.

4.3. *Stationary resources and π-Nodes (Freight Grid)*

In general, networks form a basis of various structures such as the internet, which is made of a network of servers. Similarly, a network of hubs (terminals, ports, warehouses …) connected by arcs (IWW, roads, rails) forms the freight network. However, when considering PI as the metaphor of the digital internet, real world fixed, transshipment, handling, variable cost aspects should be considered as the digital internet movements incur negligible values and minimum waiting times at nodes. Hubs – more specifically inland terminals – infer an integrative role where the feeds from LSPs, terminal operations and road-IWW-rail networks should be combined. In this regard, route prediction algorithms are necessary for calculations of ETAs (Dobrkovic et al. 2016) facilitated by cargo peak prediction algorithms at terminals (Nabais, Benítez, and Botto 2015) and dynamic behaviours among deep-sea terminals and inland terminals (Li, Negenborn, and De Schutter 2015 and 2017; Walha et al. 2016). RFID structures used in manufacturing for better visibility (Zhong, Xu, and Lu 2016) and proactive and 'smart' object solutions within nodes such as warehouses (Sallez et al. 2016; Tran-Dang, Krommenacker, and Charpentier 2017) can facilitate integration of external movements outside of hubs with movements and developments inside of hubs. Synchromodal algorithmic solutions that tackle external developments such as lower water levels or rail strikes (Dobrkovic et al. 2016) have the potential to create more resilient supply chain structures when fused with factory production disruptions (Yang, Pan and Ballot 2017a) in geographical regions with access to rail and IWW terminals. Transparency and identification of overlapping flows are imperative in order to learn about existing available capacities. Interregional synchromodal flows should thus be linked with higher density networks (Pan et al. 2015) by making use of earlier mentioned RFID structures or IoT-enabled infrastructures (Qiu et al. 2015) to react in an active manner and group accordingly to reduce loading and delivery times at switching points. Shared and cooperative consumption of assets are of high importance and certain standard coordination protocols have to be first established to facilitate bundling or transition between constituents without imposing special closed collaboration contracts inaccessible by other service providers. Therefore, network operators need to integrate their traffic management systems to achieve more efficient use of the arcs leading to reduced network congestion and better informed decisions with regard to route selection and planning, adding to less delays. This type of data exposure is imperative for real-time enabled response modelling and would provide the necessary data for more holistic and realistic models. Studies concerning control towers (Mes and Iacob 2016) information technology (IT) needs and semantics (Hofman et al. 2016) will gain greater importance with the advent of data analytics (big data). Such IT needs are also observed in the qualitative analyses of (Harris, Wang, and Wang 2015; Simmer et al. 2017).

5. Discussion and future research directions

5.1. *Models and real-time data*

The internal and external system perturbations have become major topics which are reflected in both, the PI and Synchromodality related research. However, most models, except 2 PI papers focusing on empirical experiments, test and respond to these perturbations assuming the service providers have access to demand data, real-time information of different modes and also the ability to integrate transport volume. This is still unrealistic since rail, IWW and road segments lack integrated data platforms. The lack of interoperability and current use of incompatible software also hinders the development of holistic synchromodal services at a national level, not to mention multinational. The latter is being addressed for IWW by European River Information Systems (RIS) to acquire dynamic information sharing between countries. Since synchromodal planning is to be done as late as possible, which nearly merges the planning and execution horizons, information related to real-time developments for responsive adaptation is crucial. However, real-time response modelling needs more attention as disturbed flows cannot be switched and transported ad hoc without additional costs. An option is to develop new approaches that bundle disturbed flows with long-lead time goods or similarly disturbed flows to make the system financially feasible. In other words, once a truck breakdown occurs or the network developments are not optimal to transport a given payload, an option would be to switch modes at a terminal. But as the capacity of trains or barges is larger, they will not depart unless 80% of capacity is reached; the disturbed payload would have to be combined with other containers at the terminal to fill the larger capacity; this can result in a new service or a higher fill rate of an existing service. Furthermore, switching has to be allowed together with mode-free booking so that the transport execution resembles the one of the PI certified network flow where LSPs share their capacities and create a network of logistics networks.

As for the infrastructural network, developments on arcs are assumed and synthesised due to unavailable or unaffordable data. Several Geographic Information System platforms can integrate API's from different sources at one point, but the real-time nature of the data cannot be used as input for simulations since it is designed for displaying purposes. For the time being, the polylines cannot feed the real-time developments, such as traffic on road segments, into simulations which is why the historical data is being used instead. Therefore, the alternative for researchers appears to be to model the phenomena offline by employing assumptions and highly synthesised environments. Another challenge is to determine how real-time can real-time be. More specifically, what is real-time for one application does not necessarily have to be real-time for another application. Some data is updated every day and some every hour, or minute. For instance, if a road segment takes 15 minutes to update and the weather forecast 1 hour, the decision will not be accurate due to the inconsistent data flows. Therefore, if the PI and synchromodal transport models want to deploy real-time aspects, the data from infrastructural network sensors, RFID/active tags at warehouses, GPS locations of transport means, disturbance notifications … have to improve temporal aligned in order to avoid data volatility and low quality of decisions. The decision makers should also take into account whether, for instance, 1 hour data is sufficient for making 10 minute changes.

5.2. *Centralise the dencentralised or decentralise the centralised?*

Having real-time visibility at all levels and continuous track & trace (not merely on a point-to-point basis) will be key in the upcoming future which will allow for monitoring of stock, inventories and in-house processes of hubs as well as current statuses of moving assets and states of their corresponding infrastructures such as rails, IWW and roads. In this regard, visibility and data transparency have the potential to reduce uncertainties that are depicted by models via probability distribution functions, etc.

To explore the potential of synchromodality and the PI, the freight transport research field needs to re-evaluate the current system applications with regard to often used routes, overlapping flows, available resource capacities, facility locations and communication structures in order to optimise them in an integrated manner. A crucial elements are the scope and tendencies of our reviewed papers that appear to have different end-goals. Figure 4 is to delineate these by providing the evolution of the papers' themes. It can be inferred that the PI (left) started from a grand holistic vision in 2010. Nevertheless, the PI papers appear to have a decentralising tendency in terms of research and applications; papers in 2014 address mainly the box design, publications of 2015 involve interconnecting hubs, transparency and decentralised/local asset sharing, 2016 themes address automation, decentralised price models at hubs, cities and cloud computing at hubs. The most recent papers validate our claim as the themes concern more decentralised hubs and their local optimisation and activeness of smaller containers.

On the other hand, synchromodality research has a counter tendency (Figure 4, right) to centralise the current system. Starting from the static and inflexible intermodal solutions, synchromodal papers introduce more dynamic elements in the planning and mode switching where, at the beginning, the flexibility was abstractly formulated. However, since 2015 the research shows studies with centralised tendencies that are achievable only via control towers so that ports, terminal and modes have a single reference point for service integration and container allocation. In practice, these control towers

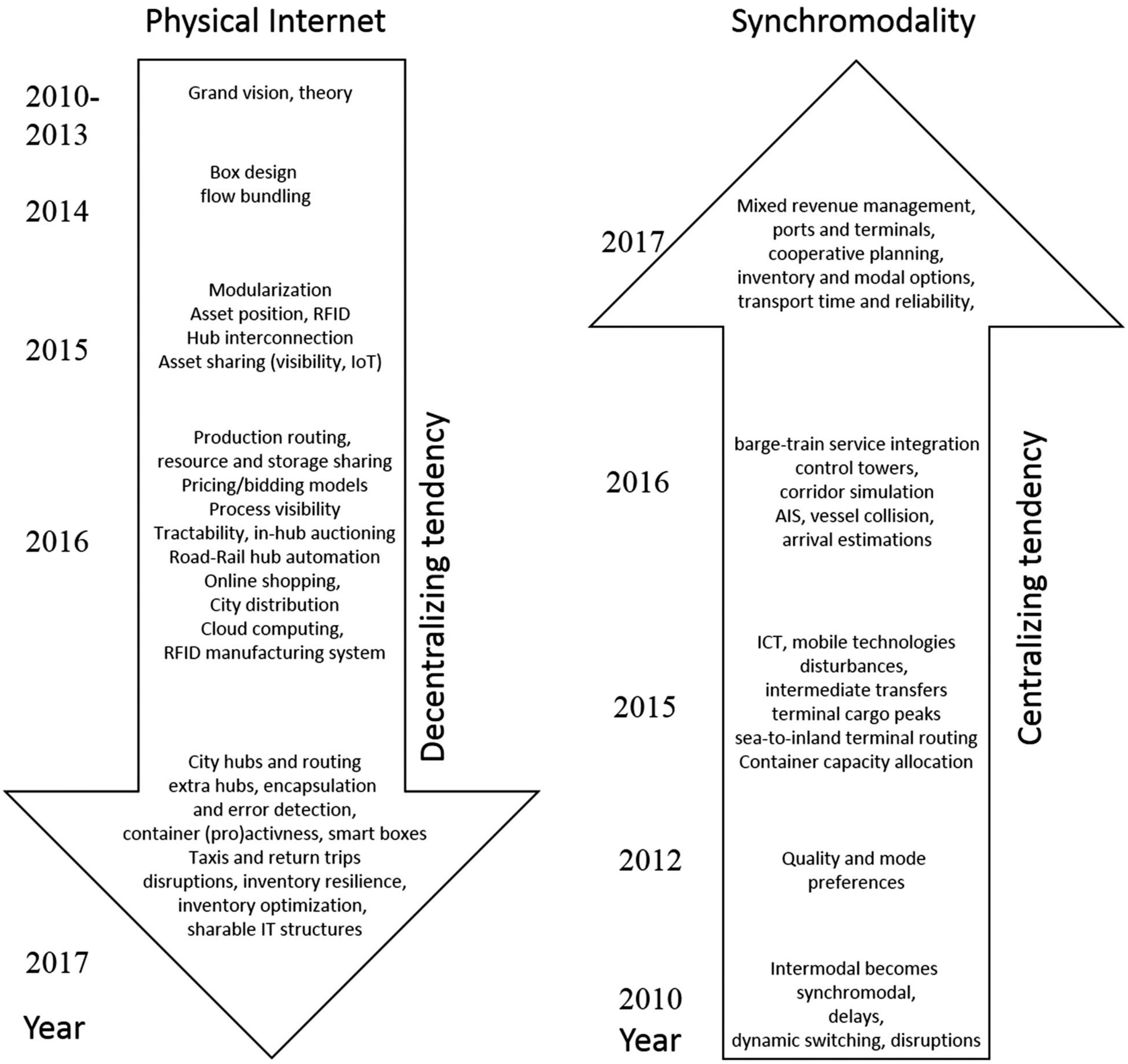

Figure 4. Illustration of reviewed-paper themes and their perceived tendencies.

vary as well; practitioners make us of port community systems, LSPs have also their own proprietary control towers who expose their data only to their clients or sub-contractors.

By pointing out these diverging tendencies of the 2 concepts, we pose the following questions that should be considered by researchers and practitioners in future developments:

(1) Should the decentralised physical internet applications be more centralised? Or should the centralised control towers be more decentralised? This question relates to interconnectivity of the production and freight transport systems since, firstly, local physical internet flows should be connected to synchromodal corridors to create critical mass for trains and barges, and induce a positive modal shift. Secondly, PI decentralised application should interact with synchromodal control towers so that the latter has less point-to-point tracking and becomes aware of spatial and temporal attributes of newly incoming orders of products and their transportation needs, etc.
(2) How should such a transparent and visible system look like and who should maintain it? The European commission is investing a significant amount of resources in Trans-European Transport Network (TEN-T) that covers 9 main corridors. Should there be 9 corridor capacity management systems (governed by Alliances such as the Interregional

Alliance for the Rhine-Alpine Corridor to name one) that facilitate synchromodal planning, and should they be connected to local manufacturing and distribution systems studied by the physical internet?

(3) Who will take the initiative; should it be the large shippers, corridor managers, carriers or LSPs? What objectives will be prioritised? As a matter of fact, shippers and LSPs have their own objectives determined by cargo type which can be more cost or time sensitive. Another aspect is the environmental footprint of the containers. In terms of congestion and bottlenecks, corridor operators may want to optimise the corridor network flow, but shippers and LSPs may want to optimise their own flows; what type of new consensus-seeking algorithms should be developed?

(4) Are the new dynamic and flexible elements in both concepts going to make the predictable static flows more unpredictable? For instance, in case of low water levels, everybody will want to use rail or road which may result in negative effects in other parts of the infrastructure. More advances algorithms should be developed to consider the potential emerging phenomena that can cause a butterfly effect in other parts of the distribution system.

To answer our research question (Are the current synchromodal and PI research streams well intertwined in order to meet the visions and goals set by ALICE and the European Commission?), the ongoing research streams are not intertwined at all as they appear to follow their own individual threads. The reviewed papers prove this disconnection as synchromodal research appears ignore the PI vision, and PI research lacks sufficiently sound synchromodal parts. The disconnected research lines need to be connected so that new models and simulation approaches may manifest faster. Researches can use this literature review to find potential similarities in their ongoing research, and contribute to novel applications and modelling practices by utilising the existing ones presented herein.

To elaborate further on our answer, the main observed obstacle standing between the holistic system vision and currently used applications is the scattered and fragmented nature of different system solutions used for operational and optimisation problems such as terminal operating systems, supply chain execution tools, enterprise resource planning systems, fleet and freight management tools, field force automation and various port community systems. The freight transport system unification will be possible when the port and terminal flows are overlaid with supply chain control towers, and the diverse multidimensional scale of the diverse tools are standardised and made compatible. This review has provided an assessment based on which it can be inferred the research field is slowly approaching this kind of system unification. But to meet the holistic view and interconnected logistics processes within the PI supply chain, it is necessary to develop more business cases, methods and tools for multi-stakeholder platforms and models that would lead to information exchange, monitoring of the supply chain, tracking of orders on routes and revenue sharing in horizontal collaboration. Thus a better proof of concepts is still required in order to demonstrate the feasibility of the synchromodal and PI ideas for future investments and their right direction. Last but not least, PI and synchromodal transport utilise different methods used by various scholars that have different background such as engineering, mathematics, computer science, geography, economics, business management, etc. Therefore, future projects and initiatives should consider the interdisciplinary nature of the problem as PI and synchromodal transport cover different dimensions and actors.

7. Conclusion

Despite the integrated roadmap of ALICE, the physical internet and synchromodal concept research streams are rather detached. Our work offers a more profound understanding of the current state of the research streams and exposes the emerging methods and technologies that could bring the PI concept and its synchromodal part closer to reality. We examined the synchromodal and PI state-of-the-art models together with their designs, methodologies and findings published in journal papers. The findings of this paper yield no integrative elements between PI and synchromodality as they both merely coexist in parallel and address different dimensions, scales and levels of abstraction. Furthermore, the paper identifies potential synergies, future research directions and critical questions to be considered by modellers, developers and policy makers. In general, it is necessary for researchers, who come from different fields with different backgrounds, to engage in cooperation and jointly carry out projects to meet the very diversified physical internet vision which synchromodal transport is an imperative part of. The research community should thus not work in silos; similar problem should concern industrial players who should expose their data to the research community so that their research models are grounded by data. Such a reinforcement loop will help researchers to limit assumptions and uncertainties, whereas the industry sector will gain richer insights regarding hidden possibilities and opportunities. This paper mainly focuses on the relevance these two concepts have within Europe; future research could cover broader worldwide applications and also consider other concepts such as ‘Freight Fluidity’ which is of high relevance in Canada, USA and Mexico. Future research could also extend our work by analysing the cooperation/collaboration fiber among LSPs as our analysis does not touch upon this matter in great detail.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by Research Foundation Flanders (FWO) – Doctoral grant for strategic basic research.

References

ALICE. 2017. Alliance for logistics innovation through collaboration in Europe. Retrieved from: http://www.etp-logistics.eu/.

Ambra, T., D. Meers, A. Caris, and C. Macharis. 2017. "Inducing a new Paradigm Shift: A Different Take on Synchromodal Transport Modelling." In *4th International Physical Internet Conference*, edited by C. Landschutzer, 4–18. [1] GrazAustria: Technischen Universitat Graz.

Behdani, B., Y. Fan, B. Wiegmans, and R. Zuidwijk. 2016. "Multimodal Schedule Design for Synchromodal Freight Transport Systems." *European Journal of Transport and Infrastructure Research* 16 (3): 424–444.

Bektas, T., and T. Crainic. 2007. "A Brief Overview of Intermodal Transportation." In *Logistics and Engineering Handbook*, edited by G. Taylor, 1–16. Montreal: CIRRELT.

Bendul, J., and T. Erfurth. 2017. "Transportation Time and Reliability in Intermodal Transport Chains." *International Journal of Transport Economics* 44 (2): 257–271.

Bock, S. 2010. "Real-time Control of Freight Forwarder Transportation Networks by Integrating Multimodal Transport Chains." *European Journal of Operational Research* 200 (3): 733–746.

Bontekoning, Y., C. Macharis, and J. Trip. 2004. "Is a new Applied Transportation Research Field Emerging? – A Review of Intermodal Rail–Truck Freight Transport Literature." *Transportation Research Part A: Policy and Practice* 38 (1): 1–34.

Caris, A., C. Macharis, and G. K. Janssens. 2008. "Planning Problems in Intermodal Freight Transport: Accomplishments and Prospects." *Transportation Planning and Technology* 31 (3): 277–302.

Chang, E., E. Floros, and A. Ziliaskopoulos. 2007. An Intermodal Time-Dependent Minimum Cost Path Algorithm *Dynamic Fleet Management* (pp. 113-132): Springer.

Chen, C., S. Pan, Z. Wang, and R. Y. Zhong. 2017. "Using Taxis to Collect Citywide E-Commerce Reverse Flows: A Crowdsourcing Solution." *International Journal of Production Research* 55 (7): 1833–1844.

Christiansen, M., K. Fagerholt, B. Nygreen, and D. Ronen. 2007. "Maritime Transportation." In *Handbook in OR & MS. Vol. 14*, edited by C. Barnhart, and G. Laporte, 189–284. Amsterdam: Elsevier .

Crainic, T. G., and B. Montreuil. 2016. "Physical Internet Enabled Hyperconnected City Logistics." *Transportation Research Procedia* 12: 383–398.

Darvish, M., H. Larrain, and L. C. Coelho. 2016. "A Dynamic Multi-Plant lot-Sizing and Distribution Problem." *International Journal of Production Research* 54 (22): 6707–6717.

Dobrkovic, A., M.-E. Iacob, J. van Hillegersberg, M. R. Mes, and M. Glandrup. 2016. "Towards an Approach for Long Term AIS-based Prediction of Vessel Arrival Times." In *Logistics and Supply Chain Innovation*, edited by H. Zijm et al., 281–294. Dortmund: Springer.

Dong, C., R. Boute, A. McKinnon, and M. Verelst. 2017. Investigating synchromodality from a supply chain perspective. *Transportation Research Part D: Transport and Environment*. http://www.sciencedirect.com/science/article/pii/S136192091630387X.

Durach, C. F., J. Kembro, and A. Wieland. 2017. "A New Paradigm for Systematic Literature Reviews in Supply Chain Management." *Journal of Supply Chain Management* 53 (4): 67–85. https://onlinelibrary.wiley.com/doi/abs/10.1111/jscm.12145.

EC. 2006. "Keep Europe Moving: Sustainable Mobility for Our Continent: Mid-Term Review of The European Commission's 2001 Transport White Paper." Office for Official Publications of the European Communities.

EC. 2011. *White Paper on Transport: Roadmap to a Single European Transport Area: Towards a Competitive and Resource-Efficient Transport System*. Brussels: Publications Office of the European Union.

Fazili, M., U. Venkatadri, P. Cyrus, and M. Tajbakhsh. 2017. "Physical Internet, Conventional and Hybrid Logistic Systems: a Routing Optimisation-Based Comparison Using the Eastern Canada Road Network Case Study." *International Journal of Production Research* 55 (9): 2703–2730.

Ghiani, G., F. Guerriero, G. Laporte, and R. Musmanno. 2003. "Real-time Vehicle Routing: Solution Concepts, Algorithms and Parallel Computing Strategies." *European Journal of Operational Research* 151 (1): 1–11. http://www.sciencedirect.com/science/article/pii/S0377221702009153.

Harris, I., Y. Wang, and H. Wang. 2015. "ICT in Multimodal Transport and Technological Trends: Unleashing Potential for the Future." *International Journal of Production Economics* 159: 88–103.

Hofman, W., M. Punter, H. Bastiaansen, E. Cornelisse, and S. Dalmolen. 2016. "Semantic Technology for Enabling Logistics Innovations – Towards Intelligent Cargo in the Physical Internet." *International Journal of Advanced Logistics* 5: 58–69.

Kong, X. T., J. Chen, H. Luo, and G. Q. Huang. 2016. "Scheduling at an Auction Logistics Centre with Physical Internet." *International Journal of Production Research* 54: 2670–2690.

Landschützer, C., F. Ehrentraut, and D. Jodin. 2015. "Containers for the Physical Internet: Requirements and Engineering Design Related to FMCG Logistics." *Logistics Research* 8 (1): 1–22.

Li, L., R. R. Negenborn, and B. De Schutter. 2015. "Intermodal Freight Transport Planning – A Receding Horizon Control Approach." *Transportation Research Part C: Emerging Technologies* 60: 77–95.

Li, L., R. R. Negenborn, and B. De Schutter. 2017. "Distributed Model Predictive Control for Cooperative Synchromodal Freight Transport." *Transportation Research Part E: Logistics and Transportation Review* 105: 240–260.

Lin, and C.-Y.Cheng. 2016. "Case Study of Physical Internet for Improving Efficiency in Solar Cell Industry." *Journal of Ambient Intelligence and Humanized Computing*: 1–10.

Lin, Meller, R. D. Ellis, K. P. Thomas, L. M. & Lombardi, and B. J. 2014. "A Decomposition-Based Approach for the Selection of Standardized Modular Containers." *International Journal of Production Research* 52 (15): 4660–4672.

Macharis, C., and Y. M. Bontekoning. 2004. "Opportunities for OR in Intermodal Freight Transport Research: A Review." *European Journal of Operational Research* 153 (2): 400–416.

Maslarić, M., S. Nikoličić, and D. Mirčetić. 2016. "Logistics Response to the Industry 4.0: The Physical Internet." *Open Engineering* 6 (1): 511.

Mathisen, T. A., and T.-E. S. Hanssen. 2014. "The Academic Literature on Intermodal Freight Transport." *Transportation Research Procedia* 3: 611–620.

Mes, M. R., and M.-E. Iacob. 2016. Synchromodal Transport Planning at a Logistics Service Provider *Logistics and Supply Chain Innovation* (23–36). Springer.

Mohamed, B. I., W. Klibi, O. Labarthe, J.-C. Deschamps, and M. Z. Babai. 2017. "Modelling and Solution Approaches for the Interconnected City Logistics." *International Journal of Production Research* 55 (9): 2664–2684.

Montreuil, B. 2011. "Toward a Physical Internet: Meeting the Global Logistics Sustainability Grand Challenge." *Logistics Research* 3 (2-3): 71–87.

Montreuil, B., R. D. Meller, and E. Ballot. 2010. "Towards a Physical Internet: the Impact on Logistics Facilities and Material Handling Systems Design and Innovation." *Progress in Material Handling Research* 40: 305–327.

Montreuil, B., R. D. Meller, and E. Ballot. 2013. *Service Orientation in Holonic and Multi Agent Manufacturing and Robotics*. New York: Springer.

Montreuil, B., J.-F. Rougès, Y. Cimon, and D. Poulin. 2012. "The Physical Internet and Business Model Innovation." *Technology Innovation Management Review* 2 (6): 32.

Nabais, Negenborn, R., R. C. Benítez, and M. A. Botto. 2015. "Achieving Transport Modal Split Targets at Intermodal Freight Hubs Using a Model Predictive Approach." *Transportation Research Part C: Emerging Technologies* 60: 278–297.

OECD. 2015. *ITF Transport Outlook 2015*. http://www.oecd.org/publications/itf-transport-outlook-2015-9789282107782-en.htm.

Pan, S., and E. Ballot. 2015. Open Tracing Container Repositioning Simulation Optimization: A Case Study Of Fmcg Supply Chain *Service Orientation in Holonic and Multi-agent Manufacturing* (pp. 281-291). Springer.

Pan, S., E. Ballot, G. Q. Huang, and B. Montreuil. 2017. "Physical Internet and Interconnected Logistics Services: Research and Applications." *International Journal of Production Research* 55 (9): 2603–2609.

Pan, S., M. Nigrelli, E. Ballot, R. Sarraj, and Y. Yang. 2015. "Perspectives of Inventory Control Models in the Physical Internet: A Simulation Study." *Computers & Industrial Engineering* 84: 122–132.

Perboli, G., S. Musso, M. Rosano, R. Tadei, and M. Godel. 2017. "Synchro-modality and Slow Steaming: New Business Perspectives in Freight Transportation." *Sustainability* 9 (10): 1843.

Pleszko, J. 2012. "Multi-variant Configurations of Supply Chains in the Context of Synchromodal Transport." *LogForum* 8 (4): 287–295.

Qiao, B., S. Pan, and E. Ballot. 2016. "Dynamic Pricing Model for Less-Than-Truckload Carriers in the Physical Internet." *Journal of Intelligent Manufacturing* 26: 1–13.

Qiu, X., H. Luo, G. Xu, R. Zhong, and G. Q. Huang. 2015. "Physical Assets and Service Sharing for IoT-Enabled Supply Hub in Industrial Park (SHIP)." *International Journal of Production Economics* 159: 4–15.

Reis, V. 2015. "Should we Keep on Renaming a + 35-Year-old Baby?" *Journal of Transport Geography* 46: 173–179.

Sallez, Y., S. Pan, B. Montreuil, T. Berger, and E. Ballot. 2016. "On the Activeness of Intelligent Physical Internet Containers." *Computers in Industry* 81: 96–104.

Sarraj, R., E. Ballot, S. Pan, D. Hakimi, and B. Montreuil. 2014. "Interconnected Logistic Networks and Protocols: Simulation-Based Efficiency Assessment." *International Journal of Production Research* 52 (11): 3185–3208.

Simmer, L., S. Pfoser, M. Grabner, O. Schauer, and L. Putz. 2017. "From Horizontal Collaboration to the Physical Internet–a Case Study From Austria." *International Journal of Transport Development and Integration* 1 (2): 129–136.

SteadieSeifi, M., N. P. Dellaert, W. Nuijten, T. Van Woensel, and R. Raoufi. 2014. "Multimodal Freight Transportation Planning: A Literature Review." *European Journal of Operational Research* 233 (1): 1–15.

Sternberg, H., and A. Norrman. 2017. "The Physical Internet–Review, Analysis and Future Research Agenda." *International Journal of Physical Distribution & Logistics Management* 47 (8): 736–762.

Tavasszy, Behdani, and Konings. 2015. *Intermodality and Synchromodality.* Available at SSRN 2592888.

Tavasszy, Janssen, van der Lugt, and Hagdom. 2010. *Verkenning Synchromodaal Transportsysteem*. Delft: TNO in opdracht van Ministerie van Infrastructuur en Milieu.

Tran-Dang, H., N. Krommenacker, and P. Charpentier. 2017. “Containers Monitoring Through the Physical Internet: a Spatial 3D Model Based on Wireless Sensor Networks.” *International Journal of Production Research* 55 (9): 2650–2663.

UNECE. 2001. *Terminology on Combined Transport*. Geneva: United Nations.

UNECE. 2009. *Illustrated Glossary for Transport Statistics*. Luxembourg: Publications Office of the European Union.

Van Der Vorst, J. G., R. Ossevoort, M. De Keizer, T. Van Woensel, C. N. Verdouw, E. Wenink, and R. Van Willegen. 2016. DAVINC 3 I: Towards Collaborative Responsive Logistics Networks in Floriculture *Logistics and Supply Chain Innovation* (pp. 37-53): Springer.

van Riessen, Negenborn, R. R., and R. Dekker. 2017. “The Cargo Fare Class Mix Problem for an Intermodal Corridor: Revenue Management in Synchromodal Container Transportation.” *Flexible Services and Manufacturing Journal* 29 (3-4): 634–658.

van Riessen, Negenborn, R. R., R. Dekker, and G. Lodewijks. 2015a. “Service Network Design for an Intermodal Container Network with Flexible Transit Times and the Possibility of Using Subcontracted Transport.” *International Journal of Shipping and Transport Logistics* 7 (4): 457–478.

van Riessen, Negenborn, R. R., G. Lodewijks, and R. Dekker. 2015b. “Impact and Relevance of Transit Disturbances on Planning in Intermodal Container Networks Using Disturbance Cost Analysis.” *Maritime Economics & Logistics* 17 (4): 440–463.

Venkatadri, U., K. S. Krishna, and M. A. Ülkü. 2016. “On Physical Internet Logistics: Modeling the Impact of Consolidation on Transportation and Inventory Costs.” *IEEE Transactions on Automation Science and Engineering* 13 (4): 1517–1527.

Verweij, K. 2011. “Synchronic Modalities–Critical Success Factors.” In *Logistics Yearbook Edition 2011*, edited by P. J. van der Sterre, 75–88. Rotterdam: Feico Houweling.

Walha, F., A. Bekrar, S. Chaabane, and T. M. Loukil. 2016. “A Rail-Road PI-Hub Allocation Problem: Active and Reactive Approaches.” *Computers in Industry* 81: 138–151.

Xu, Y., C. Cao, B. Jia, and G. Zang. 2015. “Model and Algorithm for Container Allocation Problem with Random Freight Demands in Synchromodal Transportation.” *Mathematical Problems in Engineering* 2015: 1–13.

Yang, Y., S. Pan, and E. Ballot. 2017a. “Mitigating Supply Chain Disruptions Through Interconnected Logistics Services in the Physical Internet.” *International Journal of Production Research* 55 (14): 3970–3983.

Yang, Y., S. Pan, and E. Ballot. 2017b. “Innovative Vendor-Managed Inventory Strategy Exploiting Interconnected Logistics Services in the Physical Internet.” *International Journal of Production Research* 55 (9): 2685–2702.

Yao, J. 2016. “Optimisation of one-Stop Delivery Scheduling in Online Shopping Based on the Physical Internet.” *International Journal of Production Research* 55: 358–376.

Zhang, Y., S. Liu, Y. Liu, and R. Li. 2016. “Smart box-Enabled Product–Service System for Cloud Logistics.” *International Journal of Production Research* 54 (22): 6693–6706.

Zhang, M., and A. Pel. 2016. “Synchromodal Hinterland Freight Transport: Model Study for the Port of Rotterdam.” *Journal of Transport Geography* 52: 1–10.

Zhong, Gong, H., C. Xu, and S. Lu. 2016. “Physical Internet-Enabled Manufacturing Execution System for Intelligent Workshop Production.” *International Journal of Signal Processing, Image Processing and Pattern Recognition* 9 (6): 121–132.

Zijm, H., and M. Klumpp. 2017. *Future Logistics: What to Expect*. Bremen: Springer.

Ziliaskopoulos, A., and W. Wardell. 2000. “An Intermodal Optimum Path Algorithm for Multimodal Networks with Dynamic arc Travel Times and Switching Delays.” *European Journal of Operational Research* 125 (3): 486–502.