



PILL SOTA

OVERALL LITERATURE REVIEW FOR PILL

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1 Introduction

Physical Internet (PI) is an emerging and innovative concept of future logistics and supply chain management. It has gained more and more attention from both academia and industry since it is formally published and promoted in 2011 (Montreuil, 2011). On the roadmap of ALICE (ALICE, 2019; see Figure 1), PI is deemed as a crucial stage between 2030 to 2040 towards the European zero-emission goal in 2050, indicating that its importance has been acknowledged at a European level.

There are still some imperfections in the current logistic network and supply chain in terms of social, environmental and financial aspects, and PI intends to take a step forward to a more sustainable scheme inspired by the digital internet (DI). For example, in a PI model, a route can usually be treated as segments between nodes, mimicking the data routing between routers in DI, and if a disruption occurs (order cancellation, weather changes, etc.), the route should be able to change adaptively, corresponding to the dynamic routing in DI.

To achieve the expected functions, PI relies greatly on information and communication technology (ICT). This entails the change to intelligent agents (e.g., vehicles, containers), application of the internet of things (IoT), an information system to manage and make use of data etc. However, there are few existing guidelines available regarding what a PI information system could be like, and how PI will play its role in the real world. This is the reason why this project, Physical Internet Living Lab (PILL) is launched.

PILL aims to build a prototype of the PI information system. Specifically, it focuses on the transition to higher transparency and visibility of cargo containers so as to manage and monitor the cargo flow and the movement of the assets, as well as includes maritime ports into consideration. PILL has a vision toward the future as we wish to pave the way for PI and make it easier for future companies to access the power of PI through this project. To be able to build a proper model, PILL has more than 30 outstanding stakeholders on board, including shippers, logistic service providers (LSPs), technology vendors of IoT devices and information, business orchestrators, etc. These stakeholders are the key players in the network, who provide information to build the model, allow the possibilities to validate the model in reality and generate practical value. Backed by the stakeholders, PILL will build a logistic model to mirror the real-world scenario and create added value by devising a suitable information system architecture with specifications on the protocols and standards for future developments. To better justify the added value, PILL has periodical validation on a yearly basis. We will explore the uncharted benefits of connecting the epistemological silos of the logistic practitioners.

In the remainder of this document, the general timeline of the development of PI is reviewed. Then among the selected literature, a thematic review focusing on three aspects of PI research will be reviewed, which are the modelling methods, routing algorithms and ICT. Next, according to the paper reviewed, a discussion is made about the logistic modelling and information system design. In the end, conclusions are drawn with the consideration of PILL.

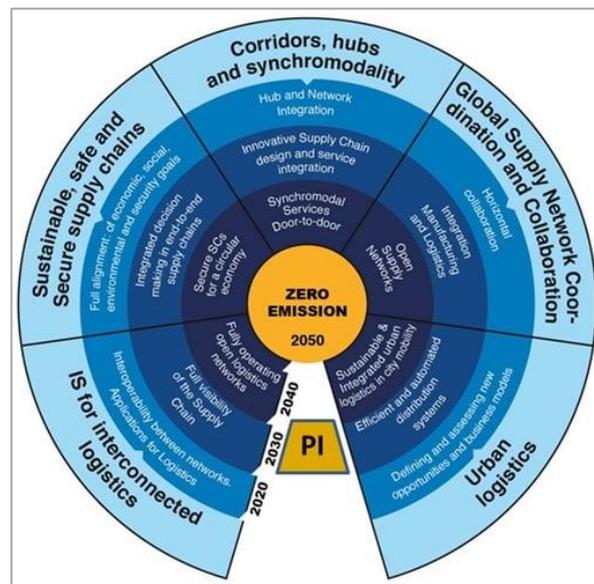


Figure 1. ALICE roadmap of zero-emission goal (ALICE, 2019)

2 Methodology

The aim of this review paper is to provide an insight into the state-of-the-art PI research by reviewing the recently published journal articles. This review paper follows the systematic reviewing process provided by Palmatier *et al.* (2018) consisting of 6 steps: topic formulation, study design, sampling, data collection, data analysis and reporting.

According to Ambra *et al.* (2019), researches on PI have become popular since 2010. Our searching scope thus ranges from 2010 to 2020 so as to have an overview of the research trend. Besides, some papers published in 2021 are also included in the collection for supporting some conclusions in this article, but the completed collection of 2021 papers is not guaranteed as many of them are not published yet and are under repair. To ensure the quality and comprehensiveness of the studies in papers, articles from conferences, webpages, master theses, etc. are omitted and only peer-viewed journal articles in English are included in our searching scope. The selection of credible journals is according to the listed journals in Scopus CiteScore™ 2019. The papers are selected by using the key world “physical internet” in Google Scholar. This can also result in some papers from fields other than logistics, which are then examined and excluded. With the above searching methodology, we identify 79 papers in total.

Additionally, the articles are categorised and reviewed with specific focuses on agent-based modelling, routing algorithm and ICT, as these aspects are most relevant to PILL.

3 PI Development Review

3.1 Start of the concept

The concept of PI (also known as π sometimes) has been promoted based on the deficiency of sustainability and the breakthrough of the technologies. Montreuil (2011) points out the 13 unsustainability symptoms in the logistic sector, introduces the components PI system and initially justifies the superiority of the notion behind PI. Montreuil *et al.* (2010) propose the various PI-related components (see Figure 2), which still remains the main concept of PI for now, including π -containers, π -movers and π -nodes as the main categories. The size of π -containers can be more variant, which can either be as big as the standard container or small but be able to compose to a standard container for the easiness of transportation. They envision each π -container, as the standard transport unit in PI, is equipped with technologies like RFID and so that the π -containers are moved like the packets in DI. The π -containers will be handled and transported by π -movers, which refers to PI-transformed tools for moving the π -containers, such as π -vehicle, π -carrier, π -conveyor etc. While some of the π -movers are operating within a PI node, some are also link among the nodes. These "entities" are named π -hubs, and π -hubs are what π -nodes mainly refer to. Although π -node can also refer to other PI structures, like π -bridges and π -transits, π -hub is the most prominent and the research focus as PI transportation networks are often considered to be composed by PI hubs and road sectors between the PI hubs. With the components defined, Montreuil *et al.* (2012) devised a 7-layered Open Logistics Interconnection (OLI) model, imitating the standard Open System Interconnection (OSI) model and TCP/IP model in the DI. Given the theoretical designs, PI is defined as "an open global logistics system founded on physical, digital and operational interconnectivity through encapsulation, interfaces and protocols" (Pan *et al.*, 2017).

3.2 An overview of PI research

In a review paper of Ambra *et al.* (2019), a line graph is drawn (see Figure 3), showing that PI has become a popular research topic since 2015. This could be affected by the annual International Physical Internet Conference (IPIC) since 2014. This trend is verified and further sorted out by Treiblmaier *et al.* (2020), who conduct the most recent comprehensive literature review on PI and

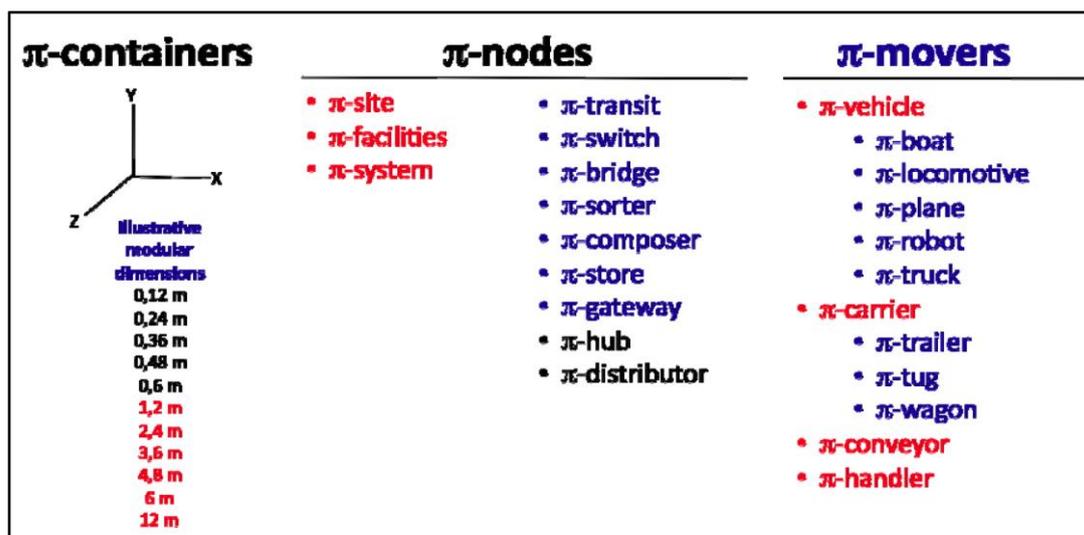


Figure 2. the components of PI (Montreuil *et al.*, 2010)

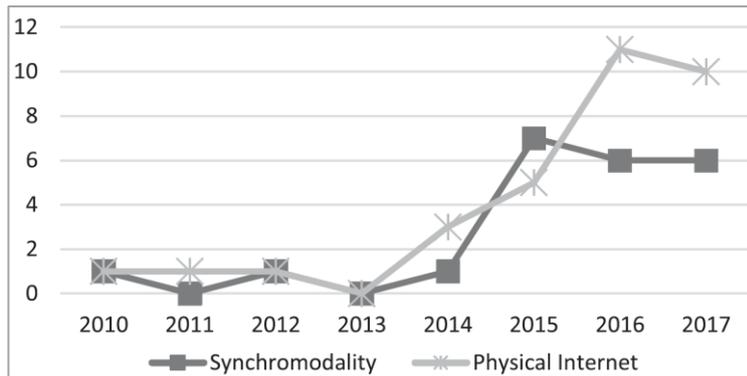


Figure 3. research trends of PI and synchronomodality (Ambra et al., 2019)

analyse the evolutionary stage of PI literature. They conclude that there are three stages: *incubation stage* (2008-2011), *exploration stage* (2012-2014) and *expansion stage* (2015-the article publication). In the *incubation stage*, research almost completely focuses on the initial concept design of PI. Examples are the articles in section **Fout! Verwijzingsbron niet gevonden..** Then, in the *exploration stage*, researchers

mainly focus on the validation of the PI concepts and assessment of proofs-of-concept. Lin et al. (2014) study the effects on the fill rate of utilising different-sized containers for a 2-stage load, i.e., a container filled with items, and a unit load (standard container/pallet) composed of containers. A lower fill rate of each individual container is concluded, whereas they argue that the second stage has a 100% fill rate, which still results in a higher overall fill rate. Sarraj et al. (2014) look at the similarities and differences between PI and the DI, justifying the theoretical foundation of PI. They also carried out a computational model with simplified assumptions, indicating that PI has the potential to reduce flow travel (amount of cargo multiplied by travel distance) and transport distance. Other possible benefits that could be brought by PI include CO2 emission, travel time and overall transportation cost (Sarraj et al., 2014b).

In the *expansion stage*, researchers mainly begin to design and assess the solutions of a certain aspect of logistics, which uniquely exist in PI rather than conventional logistics. Earlier in this stage, PI containers are studied more deeply, for example regarding their usefulness and physical design (Landschützer et al., 2015) and the intelligent features of PI containers (Zhang et al., 2016; Sallez et al., 2016; Tran-Dang et al., 2017; Gumzej et al., 2020). Some researchers also study the operational management within a PI entity in terms of, for example, road-rail PI hub scheduling (Walha et al., 2016; Vo et al., 2018; Chargui et al., 2020), inventory management (Pan et al., 2015; Yang et al., 2017a, 2017b), pricing model (Qiao et al., 2019, 2020) etc.

PI also becomes more popular and studied together with other concepts at this stage. Ambra et al. (2019) compare PI with synchronomodality, which is a developed form of multimodal transport, that makes sure all the best possible modes are chosen for each leg of a shipment (Mes and Iacob, 2016), standing for the research direction derived from conventional multimodal logistic studies. It is found that PI is usually realised with a decentralised nature in its research and focus more on logistics of lower scale (intracity) compared with synchronomodality research (centralised trend and intercity). Pujo and Ounnar (2018) connect cyber-physical system (CPS) with PI. CPS interconnects physical objects and virtual elements and enables in-between interaction like the remote control. In that sense, PI is regarded as an economic model of the cyber-physical logistical system (CPLS) in the supply chain domain due to their common digitisation and communication nature. Besides, on the basis of PI, Kant and Pal (2017) come up with the idea of the internet of perishable logistics (IoPL) as special treatment of PI for perishable goods.

In short, the research on PI stresses the following characteristics compared with conventional research on logistics and supply chain management:

- Usage of ICT and smart devices (RFID, IoT devices)
- Container bundling and composing
- Flexible treatment against disruptions (order cancellation, weather changes, traffic congestions, etc.)

- Modelling over a PI entity
- Applying interconnective technologies to business as usual
- Looking at the container fill rate and utilisation of spare resources (idle transport modes)

Moreover, it is found that the current research on maritime ports is scarce, even though the maritime ports are highly close to the design of the PI node. The current articles are mainly on the general conceptual design level (Nikolopoulou *et al.*, 2019; Fahim *et al.*, 2021). This is possible because the maritime port itself is a complicated system, in which ICT has already been widely applied in ports. Especially, if the overall modelling and assessment are to be conducted, it can often result in a too big network and too many operating scales to model. In PILL, these complications are going to be investigated.

4 Thematic Review

4.1 Agent-based modelling in the PI research

Agent-based modelling (ABM) is a computer simulation method, which is also widely used in sociology and cognitive science research. ABM helps explain the *emergence* of overall patterns and seeks the causes of each individual. Therefore, by definition, ABM functions as a tool to “conceptually bridge between the micro-level of assumptions regarding individual agent behaviours, inter-agent interactions, and so forth and the macro level of the overall patterns that result in the agent population” (Smith and Conrey, 2007). The list of collected papers regarding ABM can be found in Appendix 1.

ABM is found to be a common research method to accommodate quantitative studies of PI due to their commonality of the decentralisation structure. Sarraj *et al.* (2014b) define agents as computing modules in the PI nodes, creating several PI scenarios and comparing them with the business as usual through a case study in France. Agents are defined by functions, which are able to containerise goods, consolidate and route containers depending on their type, and each PI node has its respective agents. Their model turns out to be helpful in reducing CO2 emission and the overall cost, while the lead time raises significantly. Sallez *et al.* (2016) study the activeness of PI containers and ABM is used to define the communication and decision function of the PI containers. Walha *et al.* (2016) modelled a rail-road PI hub using ABM which integrates Best Fit Grouping Heuristic (BFGH), modified Simulated Annealing (SA) and a Decision-making Mechanism Agents Heuristic (DMAH). The agents are categorised according to their functionalities as supervisor, group and dock agents. Vo *et al.* (2018) propose an Optimized and Reactive Control Architecture (ORCA) method to control the conveyer and PI containers in a rail-road PI hub. ABM grants some predictive and reactive routing strategies for the PI containers, however, the definition of agents therein is not explained explicitly. Kin *et al.* (2018) testify the feasibility to use PI through ABM in the model SYMBIT to lower the waste of capacity in last-mile urban delivery. Different from the previous papers, agents are not completely defined by function, but entities like trucks and distribution centres are also independent agents. Similarly, Sun *et al.* (2018) also define the PI movers as agents in a rail-road PI node and confirm the effect of PI to reduce waste (fuel, capacity, etc.). Zheng *et al.* (2019) model an urban logistics system consisting of gateways, hubs, warehouses, and a cargo airport. Trucks and containers are also agents. Chargui *et al.* (2020) take advantage of the scalability of ABM, integrating 3 heuristics as different scheduling agents in a rail-road PI hub and comparing the computed results with a mixed-integer linear programming (MILP) model, which turns out to cause a very little deviation to the optimal solution. It also indicates the superiority of ABM regarding scalability.

There is something in common shown in the PI literature in the ABM aspect. So far, the research of PI mainly considers only unimodal transportation networks. When it comes to multimodal, the research scope is then confined to a single hub, which is often a rail-road hub, whereas research on ports and inland waterway (IWW) is little. Moreover, most network-level quantitative research has observed not only the good side of PI but also point out the unfavourable side effects of PI. This is mainly the trade-off between the waste of capacity and the lead time, due to the transitions between hubs, especially for urban transportation.

4.2 Routing algorithms in the PI research

Considering the routing of PI containers, it can start from the research from the last section. Those whose research scope is beyond a single hub can have some routing strategy designed. Some of the routings are done automatically by the GIS in software like AnyLogic (Kin *et al.*, 2018; Sun *et al.*, 2018). Zheng *et al.* (2019) employ the famous Dijkstra algorithm to generate the shortest paths between PI hubs. Sarraj *et al.* (2014b) choose A* as the suitable algorithm for their network of over

500 nodes and 13,000 arcs. They point out compared with DI, PI cannot route as dynamic and flexible, and the objective is not purely avoiding congestion and balancing the load.

For other PI literature, some of the routings are done by exact method for small scale networks with fewer problem-specific constraints (Venkatadri *et al.*, 2016; Fazili *et al.*, 2017; Ben Mohamed *et al.*, 2017; Hu *et al.*, 2019; Peng *et al.*, 2020). Ben Mohamed *et al.* (2017) also design a heuristic with greedy features supplemented by an improvement procedure according to their needs. In 2020, solutions other than exact methods are popularised. Kantasa-Ard *et al.* (2020) attempt to reduce the problem complexity by decomposing the network composed of PI hubs and retailers and clustering them dynamically so as to solve the routing problem in an easier way. Lai and Cai (2020) develop a heuristic consisting of a local search and simulated annealing algorithm to study the cooperation among shippers in the PI context. For the truck platooning problem, Puskás *et al.* (2020) develop a heuristic and a reinforced learning method for routing.

4.3 Information system design in the PI research

As a result of the significant importance of information exchange in PI, the design regarding a proper information system or exchange protocol has been stressed since PI was first promoted (Montreuil *et al.*, 2012). However, the actual research on this aspect was not started until the *expansion stage* (see Appendix 2 for the list of literature).

Qiu *et al.* (2015) devise a physical asset service system (PASS) and its information structure and decision support system for supply hub industrial park. Wang *et al.* (2016) proposed a PI-based manufacturing system, in which a concept of "initiative scheduling" is mentioned, suggesting that entities should be smart and take over some jobs in a decentralised way, so as to make the system more adaptive by the interactions. For a logistic network, Zhang *et al.* (2016) test the efficiency of the smart box as a form of PI container, and design the 3-layered information system, while it mainly focuses on the accommodation of container operation functions rather than the data exchanging structure. In line with the idea of initiative scheduling, Sallez *et al.* (2016) design a local scale communication framework, based on the activeness of smart containers. Additionally, at this stage, PI systems are more often proposed and validated in the case studies for manufacturers with complex operation needs, who have high error cost out of production management, such as solar cell manufacturer (Lin and Cheng, 2018), mass-customised production (Zhong *et al.*, 2016), and prefabricated construction (Chen *et al.*, 2018). This is because they have higher improvement needs, and the small scale of a manufacturer makes it easier to come true.

From then on, researchers have been focusing on designing more universal architectures for problems of a larger scale. Tran-Dang and Kim (2018) review the PI elements that had been designed and come up with a service-oriented architecture using IoT, which is composed of 4 layers – physical, network, service and interface layer. The same architecture is further developed to a PI management system (PIMS) in Tran-Dang *et al.* (2020), in which the authors also define the typical information system structures for smart IoT devices, PIMS, PI hub, etc.

Different from this conventional evolution of information system design, the blockchain has become a popular topic very recently. Meyer *et al.* (2019) point out the decentralised essence of PI and blockchain and justify the feasibility and cost-effectiveness for this new blockchain idea using the Ethereum virtual machine, as the blockchain is going to make a radically different architecture compared with the conventional information system. Due to the computational power required by blockchain, they also design a conceptual framework for different levels of PI entities to accommodate the varying computational power limitation of different types of objects. Using Ethereum, Betti *et al.* (2019) estimate the blockchain size for a transportation network, in which each entity is regarded as an agent. Their study supports that blockchain is a ready technology for PI with some minor problems (like malicious agents) to overcome. Hasan *et al.* (2021) discuss how blockchain can fit in with the requirements of PI and suggest Hyperledger Fabric and Besu as the most appropriate architectures, while they acknowledge that integration of PI and blockchain still entails much effort.

5 Discussion

5.1 Problem definition in PILL

PILL view the Flanders area as its initial testbed for PI, which consists of two seaports, Port of Antwerp and Port of Zeebrugge and their hinterland. There are intermodal hubs/warehouses that can be viewed as PI hubs, which have time-changing inventory levels. The stakeholders include truck, railway, and barge operators, in which trains and barges operate on a scheduled basis and trucks are flexible. A shipper will have its containerised goods to import or export. PILL will stress all the points listed in **Fout! Verwijzingsbron niet gevonden.** except for looking into the contents in containers to remain the simplicity to be a prototype for future PI research, i.e., the minimum transportation unit is a container. To evaluate the possibility to connect the stakeholders and maximise the benefits of utilising the acquired information, the connections will be realised in a PI digital twin to test what-if scenarios in a costless and virtual way. And a universal standard is to be identified for the interconnection. As the experiment goes on, the required aspects to be unified by a certain standard and the difficulties to build a PI network are to be revealed and solved. In the last, PILL envisions to be a successful case as a PI prototype for future research.

To model the interactive relations between the stakeholders, ABM is an ideal tool, which also has great scalability to other computing modules. The assumptions will be made greatly based on the reality settings, e.g., the availability of truck when an order generates, the slot-reservation lead time, time window, scheduled trains and barges etc., which adds a number of constraints to the problem to be solved. A good logistic model becomes a digital twin and a suitable experiment ground for interconnectivity study. In PILL the defined PI objects are PI container, PI entity, PI node and PI mover. PI containers refer to the ISO standard 20' and 40' containers with the possibility to be equipped with smart IoT devices. A PI entity is a stakeholder, who might own a few PI nodes and PI movers. A PI node could be an intermodal terminal, warehouse, factory, rail yard, etc., which are locations that can process and manage the PI containers and are also the nodes that constitute the transportation network. PI movers can refer to the types of vehicles (trucks, trains and barges) and also the handlers and conveyers in PI nodes.

5.2 Routing algorithms

Through the review in 4.1, ABM is been justified as a modelling tool. However, neither 4.1 nor 4.2 can argue for a readily available heuristic algorithm for the problem in PILL and the exact methods therein are mostly tackling networks less than 10 nodes. Therefore, it is necessary to seek other research domains for solutions.

Vehicle routing problem

In another PI project, ICONET, which is solving a similar problem to PILL, the vehicle routing problem (VRP) is referred to as a relevant problem variation (ICONET, 2020). VRP is initially stated by Dantzig and Ramser (1959), considering the VRP of petrol delivery trucks between a bulk terminal and service stations. At the end of the paper, they mention a VRP with a differentiated capacity of trucks as an extensional problem. Later on, more and more complicated assumptions are introduced, such as fleet size limitation (FSVRP), capacity limitation (CVRP), heterogeneous vehicle (HVRP, various capacity for vehicles), time window (VRPTW), backhaul planning (VRPB), dynamic order (DVRP), open vehicle route (OVRP, the vehicle does not have to return to the depot) etc. Exact methods are mostly used to tackle the variations of VRP in the earlier stage, of which exact method models are adequately reviewed, for example, CVRP in Baldacci *et al.* (2007) and VRPTW in Kumar and Panneerselvam (2012). The advantage of exact methods is that they guarantee the optimality of the solution found, however, they become intractable for larger-scale problems, especially when the problem to be treated in PILL covers all the above-mentioned VRP variants.

Kumar and Panneerselvam (2012) also point out the heuristics, meta-heuristics and hybrid algorithms to solve the variants of VRP. Recently, attention to hybrid algorithms has become more popular, especially regarding the Genetic Algorithm (for example, Ho *et al.*, 2008; Vidal *et al.*, 2012; Subramanian *et al.*, 2013). Some break the network into small clusters and solve by exact methods, some develop problem-tailored algorithms and solve the problem in multiple steps.

Synchromodality

Synchromodality is an idea derived from multimodality, which is sometimes also called synchronised intermodality. Multimodality allows goods transported by multiple modes, while intermodality make them into one contract. On top of that, synchromodality emphasises horizontal collaboration between carriers and dynamic planning that enables real-time mode changing, which is thus “a form of multimodal planning in which the best possible combination of transport modes is selected for every transport order” (Mes and Iacob, 2016). The synchromodality research has not become popular until 2015 (see Figure 3; Ambra *et al.*, (2019)).

In a recent survey of multimodal transportation (Archetti *et al.*, 2021), the logistic modelling problem in PILL can be referred to as a close variant of the multi-objective multimodal multi-commodity flow problem, and they point out that multimodality on a large network is underdeveloped. But they only mention the synchromodality research as the future solution trend to this operational problem without giving further details on algorithms. Similar to this problem, before synchromodal research is widely recognised, Ayar and Yaman (2012) study an “Intermodal Multicommodity Routing Problem with Scheduled Services”, which was defined as transporting a set of commodities using trucks and scheduled ships within the time window at the minimised cost and stocking at seaports. The problem was solved by mixed integer programming models with Lagrangian relaxation. For a double-layered transportation network of 34 seaport nodes and 66 random nodes, it generally takes over 1 hour for each solution. Later, synchromodality planning is still largely solved by exact methods (for example, Zhang and Pel (2016), Qu *et al.* (2019)) and routing become a less important issue than other topics such as scheduling, revenue management. Different from the previous synchromodality research, Ambra and Macharis (2020) propose the SYMBIT model to build a digital twin cover the numerous realistic assumptions and large network into a model.

Algorithm design

The agents defined in this ABM-based routing algorithm are both according to the PI entities (hubs, trucks, trains, barges and containers) and functions (routing and improving modules). The main feature is that the route and improvement are concluded completely by the communication between the PI nodes (hubs) in a decentralised way, which confines the computational power in the hubs and prevent from distributing the computational power to all the agents like trucks and containers. This is for scalability considerations.

Previous algorithm designs tend to view the shortest path as the objective function (e.g., in traditional VRP). However, we argue that the shortest or fastest path could not be the only or even a major objective. The main reasons of its importance are 1) shortest path planning guarantees to bring the routed objects to the destination; 2) shortest path planning correlates with vehicle cost, energy consumption, greenhouse gas (GHG) emission; 3) delivery time used to be a much more important concern than security, quality, etc. (but in modern logistics, it is not always true). These have made shortest path planning a simple and effective indicator of a route. However, if the above points are satisfied, the weight of the shortest path planning can be safely reduced. The reason for that is: 1) as a system, simply trying to deliver everything as fast as it can be is very likely to cause faster-than-necessary deliveries and waste the network resources; 2) from the stakeholders’ perspective, shortest path planning would be less attractive if the cost can be presented in a more straightforward way; 3) no unnecessary fast helps maintain social sustainability especially for the truck drivers and workers.

Therefore, a multi-objective function is proposed to compare the goodness of a route plan, in which variables could be travel distance, GHG emission, fixed/non-fixed cost of vehicles, etc. (can also according to the logistic performance indicators in Bowersox *et al.* (2019), pp.38). The wide inclusion of objectives weakens the second supporting reason for shortest path planning. Following the principles of PI, the objective function is calculated by accumulating the values added by each hub of the route segments. In that case, the parameter (weight) of the variables can be user-defined and hub-depend.

As the routing is done by ABM with extraordinary scalability, the routing can be done by one or multiple basic algorithm(s), for example, a breadth-first search (BFS) algorithm, supplemented by several auxiliary modules. The advantages of BFS are: 1) BFS is complete, i.e., a feasible route is guaranteed to be found by BFS if there exists, and routes with fewer segments (likely to be shortest) are always searched before routes with more segments, relaxing the first supporting reason for shortest path routing; 2) when the network is large, the branch-and-bound method can be applied to cut the searching space; 3) user-defined rules can be easily added in searching. BFS will make the last node request message to all the other accessible nodes, and the other nodes reply according to the constraints of their own. In this way, communication is established, which can continue as such until all the possible routes of an order are pointed out, or some user-set constraints are met. To avoid faster-than-necessary cases, users are required to input a time window for each order as a benchmark of necessity. And time window will be used for calculating a penalty function. The detailed description of the designs of the basic algorithm can be found in "The basic algorithm description" in Appendix 3. The final route will be output by comparing the objective functions of all the potential routes.

For the auxiliary algorithms, a good ABM structure that can be referred to is Chargui *et al.* (2020), in which a planning request will be broadcasted to 3 calculating agents and the best result will be sent to a synchronising agent. In PILL, agents are defined both by entities and functions. Especially, a few functional agents can be defined to accommodate the auxiliary algorithms:

- Route consulting agent. As the complicated set of constraints for the nodes take time to get computed and it is unrealistic to request message from all the nodes for each step for each potential plan for a large network, a route consulting agent can help to do an initial sift by returning a few candidate nodes to request message, calculated with most of the constraints relaxed. This can be GA as the objective function can well function as the fitness function. Also, machine learning methods can be added. The training set can be fed and the model itself can be validated both by the previous routing results.
- Random improving agent. Benefitting from the collaboration of the stakeholders, the algorithm supports replanning when an unexpected event occurs to the already planned route, such as train cancellation, capacity shortage. In that case, the route planner can be simply restarted, and related information will be sent to the affected stakeholders. However, a change on the network in the parts other than the planned routes could also bring improvement possibilities of the current route. Therefore, if a node has redundant computational power, it can call this agent and calculate the improvement possibilities for the incoming orders according to the randomly selected events that occurred recently.
- Demand forecasting agent. For truck planning, it always takes time to get to the position to pick containers, causing extra lead time. If the geographically distributed shipment demand can be modelled as time series and properly forecasted, then the trucks are more likely to be already near or at where they are needed when an order is input to the system.

In addition, multiple basic routing algorithms can be added, and all or part of them can be run in parallel according to the pros and cons of the algorithms. This could be overall managed by a coordinating agent, which is responsible for computational power management, computing time management, algorithm switcher etc.

6 Conclusion

The concept of PI has been developed into an ecosystem, in which PI concepts are well defined and a number of experiments have been carried out to prove the excellence and the potential to improve future logistics. By reviewing the existing articles from credible journals, we have a clear view of the timeline for the development of PI, especially with the focus on the ABM, routing paradigm and information system design. Moreover, it is identified that multimodal transport, especially seaport and IWW as an underexploited research direction. In this project, PILL will give insight into this direction and build a prototype in realistic settings. The main objectives are twofold: build well-performed logistic modelling as a PI digital twin and find universal and applicable standards to enable PI for future business and research practices.

There are some limitations of this article. First, because this article only collects credible journal articles, some valuable research could be overlooked, for example, the OLI model for PI is proposed in a conference paper rather than a journal (Montreuil *et al.*, 2012). But important conclusions from the papers of other sources should have also been referred to by the collected journal articles, thus constructive and milestone research are not likely to be omitted. In addition, the proposed algorithm is still to be tested by numerical experiments. Auxiliary modules and algorithm design are subject to be re-designed under the flexible framework of ABM.

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Appendix 1. ABM research in PI (sort by online publish date)

Author(s)	Year	Title	Note
Sarraj et al.	2014	Interconnected logistic networks and protocols: simulation-based efficiency assessment	Function as agent
Sallez et al.	2016	On the activeness of intelligent Physical Internet containers	Function as agent
Walha et al.	2016	A rail-road PI-hub allocation problem: Active and reactive approaches	Function as agent
Vo et al.	2018	Control of Rail-Road PI-Hub: The ORCA Hybrid Control Architecture	PI entity as agent (not specified)
Kin et al.	2018	Tackling fragmented last mile deliveries to nanostores by utilizing spare transportation capacity—A simulation study	PI entity and function as agent
Sun et al.	2018	Multiagent modelling and simulation of a physical internet enabled rail-road intermodal transport system	PI entity and function as agent
Zheng et al.	2019	Assessment of the physical internet enabled urban logistics using agent-based simulation	PI entity as agent
Chargui et al.	2020	Proposal of a multi-agent model for the sustainable truck scheduling and containers grouping problem in a Road-Rail physical internet hub	PI entity and function as agent

Appendix 2. Information exchange system research in PI (sort by online publish date)

Author(s)	Year	Title	Category
Qiu et al.	2015	Physical assets and service sharing for IoT-enabled Supply Hub in Industrial Park (SHIP)	Manufacturing: supply hub industrial park (SHIP)
Wang et al.	2016	Research on initiative scheduling mode for a physical internet-based manufacturing system	Manufacturing: general, initiative scheduling
Zhang et al.	2016	Smart box-enabled product-service system for cloud logistics	IoT PIMS: smart box, PSS, CC
Sallez et al.	2016	On the activeness of intelligent Physical Internet containers	PIMS: framework among PI containers
Lin and Cheng	2016	Case study of Physical Internet for improving efficiency in solar cell industry	Manufacturing: solar cell manufacturing
Zhong et al.	2016	Physical Internet-Enabled Manufacturing Execution System for Intelligent Workshop Production	Manufacturing: mass-customised (MC) production
Chen et al.	2018	A Physical Internet-enabled Building Information Modelling System for prefabricated construction	Manufacturing: prefabricated construction
Tran-Dang and Kim	2018	An Information Framework for Internet of Things Services in Physical Internet	IoT PIMS: data collection
Meyer et al.	2019	Blockchain technology enabling the Physical Internet: A synergetic application framework	Blockchain architecture
Betti et al.	2019	Improving Hyperconnected Logistics with Blockchains and Smart Contracts	Blockchain architecture
Tran-Dang et al.	2020	Toward the internet of things for physical internet: Perspectives and challenges	IoT PIMS: all-round tech review
Hasan et al.	2021	Blockchain Architectures for Physical Internet: A Vision, Features, Requirements, and Applications	Blockchain architecture

Appendix 3. The basic algorithm description

This can be found in a [separate document](#).