Using Agent-Based Simulation for Efficiency Assessment of Physical Internet Enabled Logistics System: Framework and Application

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Abstract: Simulation-based decision support systems for physical-internet-enabled logistics networks have been developed at an increasing rate in recent years. This work presents an agent-based simulation framework that represents the interaction between mobile recourse units and logistics infrastructure. The model attempts to capture the cause and effects of logistics operations, and is used for the evaluation of a physical-internet-enabled logistics network. One influencing factor can be changed at a time to examine its influence on system performance. This allows us to develop an understanding of which assumptions and data inputs significantly impact the model and the results. Using a case study, an open global logistics network is developed in a simulated environment by assuming that traffic participants are rational. An agent-based simulation assessment is performed to quantify the improvement options that are available through the physical internet. The results reveal that the physical internet can prevent trucks from empty driving, which has a positive effect on the sustainable development and cost-efficiency of logistical services. The developed model facilitates the analysis of operational and fleet sizing alternatives, as well as the analysis of the influence of their provisions on societal, environmental, and mobility performance at the system level.

Keywords: agent-based simulation; logistics; physical internet

1. Introduction

1.1 Containerisation of goods

Road-based transportation is critical for regional economic development, and road freight transportation performance influences many essential aspects of society (e.g. city attractiveness, service flexibility, and accessibility). Previous studies have pointed out the dependency of socioeconomic systems on road freight [1] and the need to mitigate its negative consequences [2]. Mobility in road freight transportation affects the on-time efficiency of delivery, and further influences the competitiveness of products, especially in sectors with low-margin profits and stochastic demands. Delivery efficiency has a profound impact on the financial status of supply chain operators executing logistics and transportation activities. Furthermore, road freight transportation can make significant contribution to society as a whole because it is the biggest greenhouse gas emission generator of all transportation modes [3]. Logistics innovations in road freight transportation can achieve significant improvements in trucking productivity, emission reduction, and in-cab conditions (e.g. health and safety) [4]. Despite the promises of logistics innovation, road freight transportation operations are continuously characterised by low innovation engagement (Wagner, 2008; European Commission, 2011).

Intermodal transportation facilitates collaborative delivery across modes in freight transportation. According to forecasts, the intensity of intermodal transportation is projected to grow, which highlights the growing importance of modular concepts in future delivery systems. A report by the International Transport Forum stated that the volume of international freight transportation will increase fourfold until 2050 [5]. One of the main operation technologies driving the development of intermodal transportation is the 'drop and pull' or swap-body service. Swap-body service technology utilises 53-foot semi-trailers and involves deadhead movement of the tractors in the traditional logistics system. A powered tractor continuously towing more than two carrying devices for a delivery is technically considered an integrated vehicle unit. The powered tractor will be towed with a carrying device, including a semi-trailer, trailer, and even trucks on the chassis of the container, and then drag the carrying device filled with the goods to a new location or the destination. This type of trucking operation technology with standardised containers is deployed worldwide to organise intermodal transportation, and has developed into a model across different transportation means and modals.

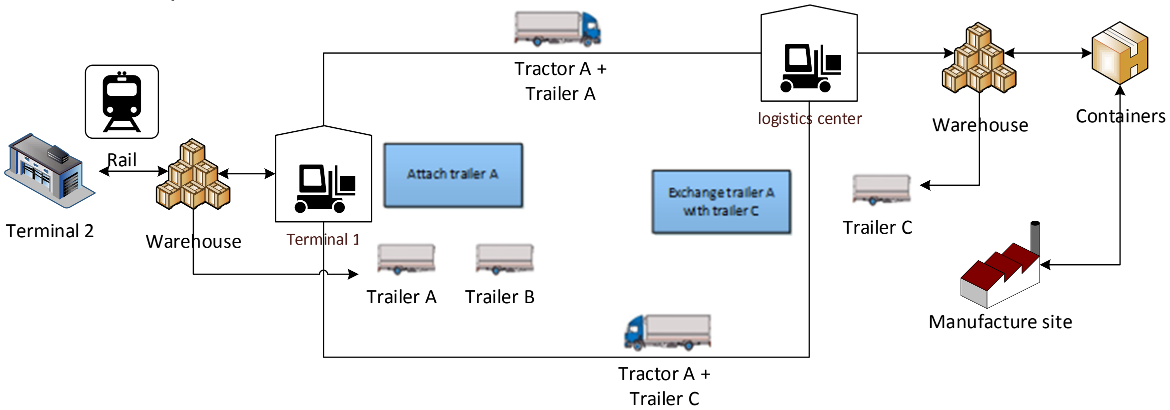

Figure 1. Containerisation of goods.

The standardisation of transportation units (e.g. modular containers) provides many opportunities to integrate transport systems. It motivates haulage firms to exchange flows and improve freight mobility to ship goods in large-scale and complex systems [6]. Supported by such trucking operations, freight corridors with goods assembly and massive shipments can be developed (e.g. the quickly growing rail-based international connection on a large geographic scale). Containerised modular goods are easily handled by different components of a freight system, and can be efficiently transshipped from road transportation to rail or ocean transportation, which possess better sustainability, and which will reduce greenhouse emissions. The improvements to efficiency and environmental impact that can be achieved by adopting a modular design for a material handling system are of interest to both freight and service providers.

1.2 Physical internet in the logistics sector

The efficient transportation of multiple and small batches/consignments of products can be realised in a distributed and smart logistics network. In parallel to the growing containerisation in the transportation industry, the physical internet, an innovative concept first introduced by Prof. Benoit Montreuil, is a positive response from the logistics sector to implement the Internet of Things in service industries. A physical internet is an open global logistics system based on physical, digital, and operational interconnectivity [7], rather than dedicated and specialised networks. The physical internet enables logistics networks to encapsulate goods in smart, environmentally-friendly, and modular vehicle units. The encapsulation of goods in modular, reusable, and smart containers has the potential to become a new paradigm for freight organisation. The standardised mobile resources in the physical internet will be mutually managed by several shippers instead of individual managers [8]. Supply chain interoperability and economic, environmental, and societal efficiency are important research highlights in the literature of the physical internet in logistics.

Previous studies emphasised the foundations of the physical internet by physical, digital, and operational interconnectivity through encapsulations, interfaces, and protocols as a solution for logistics sustainability challenges [9, 10, 11, 12, 13]. These studies identified opportunities to integrate the physical internet in the logistics sector to improve economic, environmental, and social efficiency through a technological, infrastructural, or business model innovation. An article by Science Magazine [14] stated that the physical internet will move goods much in the same way as its digital namesake moves data, and promote collaboration in developing standardised containers, common protocols and tools, and shared transportation and technological assets. A large range of methods for engineering the physical internet was reported in previous papers. A literature review concluded that 46 applications have been performed and the applied methods are generally diversified [15]. Operations research methods, including simulations, make contributions to research on the physical internet.

1.3 Simulation-based approach for the governance of complex systems

There are three main simulation paradigms available for tackling logistics issues: discrete event simulation, system dynamics, and agent-based simulation. It is commonly believed that discrete event simulation is suitable for analysing operational/tactical problems, whereas system dynamics is an ideal paradigm for strategic planning [16] and the creation of economic models. Agent-based simulation is deemed suitable for modelling interactive rules between components, and it understands how those interactions between autonomous agents affect the system. A number of recent studies addressed road freight problems based on agent-based simulation and highlighted the growing importance of using the agent-based method in the governance and planning of complex logistics systems. Holmgren et al. [17] constructed a Transportation and Production Agent-based Simulator (TAPAS) for freight analysis. In this simulator, a modular structure is applied to study zone-based freight movement flows. The case study indicated that fuel savings and a reduction in CO_2 emissions was achieved by shifting goods from road transportation to rail and ocean transportation. Caris et al. [18] addressed different cases of port locations and their impacts on network characteristics.

Several recent simulation studies analysed the rendering individual effects achieved by physical-internet-enabled systems based on the exploration of different operational scenarios. Based on a simulation model of the large-scale French food distribution supply chain, Ballot et al. [19] presented an evolutionist approach to solve the open hub network design problem. Their evolutionary approach emphasised the importance of the network design of an open hub network on enabling logistics organisation. Hakami et al. [20] developed a mobility web simulator to estimate order flow changes based on the comparison of two system states in French fast-consuming goods industry. The flow of goods in a physical-internet-enabled system reveals the structural impacts, e.g. increased number of delivery trips. The efficiency of transportation modes was identified by the significant reduction in the total travel distance. They pointed out that the physical internet profoundly renders the way physical objects are transported. Furtado et al. [21] modelled the transportation activities of tractors and the consolidation of trailers into a road train, in which various demand scenarios were tested by using the physical internet philosophy. Other simulation studies focus on efficiency assessment [22], container repositioning strategy [23], and inventory controls [24, 25].

Above all others, agent-based simulation is best suitable for modelling detailed operations in many sectors (e.g. city logistics [26], production systems [17], and marine logistics [18]) because it is the only simulation paradigm that that supports prescriptive analytics based on the interactions between individuals. Although the agent-based method is promising for the modelling and analysis of complex systems, its application in the support of managerial aspects in the physical internet, e.g. management of mobile units among horizontal collaborators in road haulage, is currently not prevalent in this sector. There is a lack of agent-based simulation frameworks that model the interactions between tractors and trailer containers. Very few simulation studies assign decentralised capacity to make containers proactive rather than passive. Generally, decision support tools are needed to assess options provided by potential technologies (e.g. physical internet) that might entirely reform the physical environment of logistics operations.

Instead of traditional trucking operations, we suggest that an open global logistics system supported by the physical internet might be a valuable option for system savings in terms of cost and improved social efficiency. This system is developed based on three prerequisites: (1) the abolishment of dedicated and pre-defined infrastructures, (2) the semi-automation of orders, and (3) real-time control of mobile resource units. Key performance indexes from a multidisciplinary perspective are calculated. The agent-based simulation framework is designed in an object-oriented manner and the focus area is the interactive rules of resource components and the modelling of the proactive trailer container agents. Similar to previous simulation studies, this work utilises data from freight operations to perform a validation of the simulation model to ensure a reliable comparison of the two states of the logistics system. A deepened analysis addresses the robustness of the simulation model to the fleet sizing of tractors.

2. An agent-based simulation framework for physical internet

This section presents an agent-based simulation framework for recreating interactive rules for different actors. Agent-based simulation is used for quantifying the improvement options made possible by the physical internet. The logistics system is a complex technical system that can be supported by a modular and changeable design [17]. Because agent-based simulation models can help us to understand the behaviour of decentralised freight systems [28], it is considered suitable and useful to construct such a decision support tool for what-if scenario explorations in physical internet applications, and for analysing sources of variations in an open distributed system. Contrary to other simulation paradigms (e.g. discrete-event simulation and system dynamics), the agent-based method utilises a modular approach to model the interaction of mobile resource units and their effect on freight performance.

Four different agents are used in the simulation model to represent producers, shippers, and mobile recourse. Those agents interact within a physical entity simulator. The physical entity simulator is based on an open source geographical information system, OpenStreetMap, which is used for synchronizing indicators related to the developed environment. The transport-related indicators are updated when delivery orders enter or sink. The virtual agents are presented to the user of the model to better understand the cause and effects of the model and input factors. Process validation is also performed based on available freight data. This is to make sure that the simulation model is validated from a business perspective, and is reliable for producing prescriptive analytics.

Logistics operations for uploading, delivery, parking, and exchange are explicitly modelled for handling inbound and outbound orders. These considerations are based on the characteristics of the investigated system. Decision making by agent is rational in the time dimension. This means that transport proposals generated by containers minimise shipment wait times. This is because on-time delivery is a commonly prioritised objective when considering logistics as a service. Utilizing the rationality of an agent to achieve minimised travel time is a worthwhile concept to explore, but it is out of the scope of this work. The assignment and allocation of resource units (e.g. manpower, vehicle units) incur costs and energy consumption, which means that freight operations between locations and the interactions between resource units eventually determine the economic and environmental sustainability at the system level. The handling of containers is triggered when a delivery request message is received. Performance indicators are calculated as the simulation model progresses. Because we are analysing a transport system, time stamps and geographical elements are used for the calculation of temporal and distance-based indicators.

We have modelled individual decision-making processes at three levels: the network level, the facility level, and the vehicular unit level. Intelligent agents capable of making decisions based on environmental conditions are developed to represent the best real-world decision making in management control, facility operations, and transportation processes. We have followed the suggestion of model construction proposed by Banks and Chwif [29], that is, constructing a model of sufficient level (not too simple, not too complex), conducting conceptualisation prior to simulation implementation, and validating the computational model gradually. At the network level, management controls address real-time fleet assignments to minimise container wait times. At the depot and terminal level, facility operations include the interaction of the temporary storage of delayed products, physical internet containers, and departures of trucks and freight trains. The tractors and containers are modelled as agents interacting with each other and with the spatial environment. These modelling perspectives are aimed to approximate reality and increase the confidence and reliability of the model-based analysis. These components are considered when developing the targeted decision support system consisting interactive user input, physical entity simulator, simulation interface, and simulation data collection and analysis for projecting freight efficiency, effectiveness, and the societal impacts of using physical internet. Two comparable scenarios are developed. In the baseline scenario, agents behave according to the classic operational practice of drop and pull transport, which involves deadhead tractor movements. The physical-internet-embedded scenario assumes that packets with embedded freight data are transferred and visible among shippers.

In order to investigate the system-level phenomena, the decision support system combines road freight data, the physical movement of goods and mobile resources, and the communication of transport units to support the strategic planning in partnering shippers and facility owners. To this end, virtual agents of (1) Depot, (2) Coordinator, (3) Tractors, and (4) Containers, all of which are independently functioning, are used to model the movement of goods and mobile resources for the multiple-scale freight handling. The tractors and coordinator are proactive agents for operational control, whereas the depot is a passive agent that acts as an infrastructure element. Containers are modelled as active agents. The activity of containers is supported by other operational recourses.

(1) The depot is a population of nodes that represents a railroad freight terminal served by intermodal transport facilities and smaller depots connected by road haulages. Nevertheless, all depots share common attributes, including the generation of freight transport demand, waiting lists, resource pools, and the calculation of key performance indicators, which are widely used in the system analysis of logistics performance. Scenario generation is controlled by a dynamic event, and historical orders are disaggregated by data adaptions. Freight demand might be satisfied by more than one container for large goods. The waiting list is the collection array of the temporarily stored products that are delayed because of the unavailability of a tractor. Resources are pools of common specified objects, which include containers and parking slots. Performance indicators document the economic and environmental measurements that change over time and are visualised through a user interface. The interface also outputs simulation data into spreadsheets.

(2) Tractors and containers are active mobile resource units and have different fleet sizes. In most situations, tractors and containers are the message receivers of production and transport orders, and react according to the specific type of order and crew assignment delivered by the coordinator. In traditional operations, the tractors and trailers are centrally managed. In this framework, we model the active containers as decentralised and non-hierarchically operated. The containers have access to the states of the rest agents, and have individual criteria for coupling with a suitable tractor in shared places. The container is the active agent that identifies the transport segment and publishes the proposal to the tractor. A routing subagent is embedded within the tractor agent to receive the proposal and motivate the tractor. Therefore, all the containers can access and update the states of the system and its components, and find the capacity to support the shipments. Raw materials will be shipped towards the processing plants. Products will then be gathered at the terminal for railway transport.

(3) The coordinator is a virtual agent that executes central management controls. The coordinator is responsible for arranging parking, uploading, offloading, and inspection. This agent receives requests to handle activities from all depots and the terminal. The coordinator is initiated with a real-time control function to appropriately select containers that meet certain criteria. The coordinator has different functionalities in the non-physical-internet-enabled network and the physical-internet-enabled network. In the non-physical-internet-enabled network, the coordinator matches transport units with requests. Information regarding the shipper, client, freight volume, and client priorities is included in the order. Once receiving an order, the coordinator will process the abovementioned items and allocate mobile resource units. Given an expected loading time, the coordinator will then pass the message to the closest tractor to pick up that particular physical internet container. Once a task is finished, both tractors and containers return empty and prepared for the next mission, and the tractor might head towards a specific location. If containers are starved at a hub, the coordinator might be programmed to trigger the repositioning of empty containers. In the physical-internet-enabled network, the coordinator is only responsible for handling activities at depots and the terminal. The identification of the route and transport segment will be carried out by each decentralised active container.

The simulation project explores real freight and structural data at the logistics web layer. These data are provided by a regional consortium of shippers and an intermodal facility owner.

Freight data include average values of weekly order volumes and freight types. The shipped goods are mainly bulk materials and are commonly assigned to more than one trailer within a delivery order. Day-to-night volume variations will be examined and populate the data generation function of the simulation model.

Overall, the process of performing a simulation experiment includes determining input data, scenario generation, running simulation experiments, and analysing output data. A simulation run of seven operation days takes 20 min on a standard personal computer.

Studies related to complex self-organizing systems use simulation methods to address the various business models, the cooperative structures, and the important presence of uncertainty and dynamics. The intermodal transport organisation is based on the modular design concept with many business constraints. The vehicle agents are frequently coupled or dissembled, and positioned to accommodate transport demands. These characteristics are in line with an agent-based model. The above agent-based model is considered to be a suitable method to simulate a dynamic study on the sources of variation.

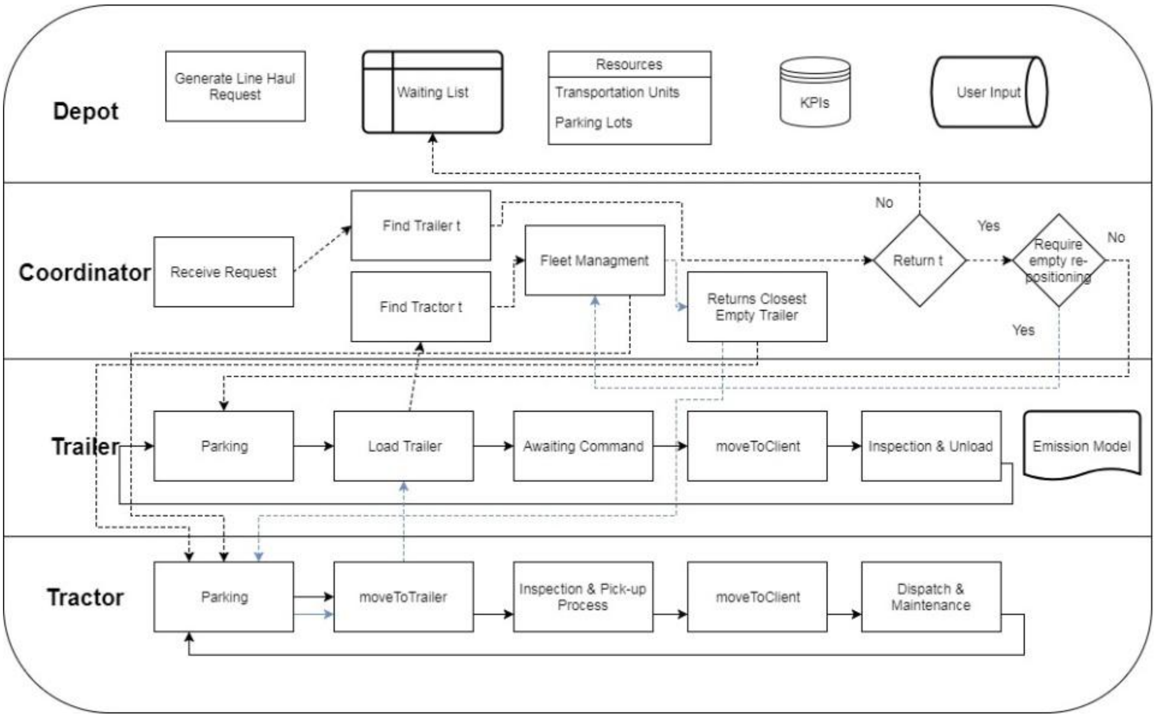

Figure 2. Schematic of the agent-based simulation framework.

3. Case study description

The original plan for the use case is a horizontal integration of upstream and downstream operations to pursue regional competitiveness in a low-margin sector. This collaboration requires a combined set of improvements in mobility and efficiency issues in the logistics network, including the containerisation and capacity expansion of a freight terminal served by rail and road links. The freight terminal functions as a single hub for all outbound and inbound flows and connects upstream shippers with different end users at the other end of the railway link. The road-based freight transport needs to eliminate congestion, delivery delays, and inefficient utilisation of tractors and trailers. Traffic congestion management could be solved by physical internet technology [34]. Spatially, the road haulage firms are located in rural areas, whereas the facility operator is located at the frontier of the city. Therefore, the logistics activities occur in at the intersection of city logistics and rural distribution. We consider the option of applying a physical internet container in this use case rather than the continuous usage of traditional passive trailers. Table 1 presents the operational data, spatial distances, shipments per tractor on each day, travel time, inspection time, and loading and offloading times. The data presented in Table 1 are used as parameters for populating the simulation model.

Several workshops on data collection, confirmation of business techniques, and discussion about possible business models have been conducted with the managing boards of the companies involved. This is deemed necessary for participatory and collaborative design of simulation models. This information is used for data and process validation of the simulation model. Data are available from August 2014 to July 2015 and includes shipments per tractor, total payload distance, and other operational details. In addition, the research group completed a survey on freight demands, transport infrastructure development plans, and citywide socio-economical attributes that have connections to the operation of the companies. Freight flows are disaggregated into daily delivery orders using a data adapter proposed by Hakimi et al. [30]. One of concerns of the shipper is fleet sizing. The supply chain operators are willing to retain a limited number of expensive assets to maintain a healthy financial stature.

Tractor operation generates indicators that include the number of kilometres travelled and CO_2 emissions. Specifically, the CO_2 emission calculation is based on the weight of the shipment, the travel distance, and a specific emission factor used in a previous study [31]. Operation cost is a global indicator composed of many components in the process of handling containers. Fore presentation convenience, the Yuan (¥) currency is used for costs. Indicators, formulations, and units are presented in Table 2. The constants are obtained from the contextual facts of the use case. The indicators are integrated with the simulation model and exported after the experiment for data processing and presentation in Matlab.

Table 1. Operational fact data

Indicators	terminal-depot 1	terminal-depot 2	terminal-depot 3	terminal-depot 4	terminal-depot 5	terminal-depot 6	terminal-depot 7
Spatial distance (km)	120	136	220	92	73	115	34
Freight types at terminal	Oil supplies	Oil supplies	Oil supplies	Construction material	Hardware electrical materials	Processing casing	Machinery equipment and accessories
Freight types at depot	Coal; postal services	Coal; postal services	Coal; postal services	Agricultural products	Agricultural products	Agricultural products	Agricultural products
Travel time (h)	2.4	2.72	4.4	1.84	1.46	2.3	0.68
Inspection time (h)	0.5	0.5	0.5	0.5	0.5	0.5	0.5
loading time (h)	3	3	3	3	3	3	3
Shipments per tractor on each day	1.54	1.42	1.02	1.80	2.03	1.58	2.75

Table 2. Input and performance indicators (Note: constants correspond to the practical setting of the investigated system)

Input/performance indicator	**Fact/Formulation**
Container capacity in weight	30 ton
Container capacity in volume	54 m^3
Vehicle kilometres travelled	$\sum_t D_t$, D_t: travel distance of tractor t. unit: km
Full loaded travel distance	$\sum_t \frac{D_{t-\text{load}}}{N_t}$, $D_{t-\text{load}}$: loaded travel distance of tractor t; N_t: number of tractors. unit: km/vehicle
Payload distance	$\sum_t \frac{D_{t-\text{load}} \times t_{load}}{N_t}$, t_{load}: weight of tractor.unit: ton-km/vehicle
Fuel consumption	$\sum_t O_t / (\sum_t D_{t-\text{load}} \times t_{load})$, O_t: oil comsumption of tractor t. unit: L/ton-km
Logistics cost	$(\sum_t O_t \times 6.90 + N_t \times 24000 + N_c \times 18000 + N_t \times 2 \times 48000 + \sum_t D_{t-load} \times t_{load} * 0.06) / (\sum_t D_{t-load} \times t_{load})$, N_c: number of containers. unit: ¥/ton-km

4. Simulation initiation, verification, and validation

The agent-based simulation framework was configured to construct the simulation and is presented in Figure 3. Virtual agents are the core of the model. For each agent, the internal decision-making process can be programmed in the Java IDE. Logic control functions represent the changes at the strategic level, and the simulator enables the switching of system states. The use of the physical-internet-enabled logistics network or traditional trucking operations is indicated by specific parameters, which is defined by the end-user before the simulation experiment is initiated. Simulation data analysis is based on the building blocks of 'dataset' and 'variable'. The 'event' building block ensures that data presentation is updated as long as the states of the agents are changed. The next paragraphs present the verification and validation of the simulation model, and are followed by the interpretation of the simulation results in the next section.

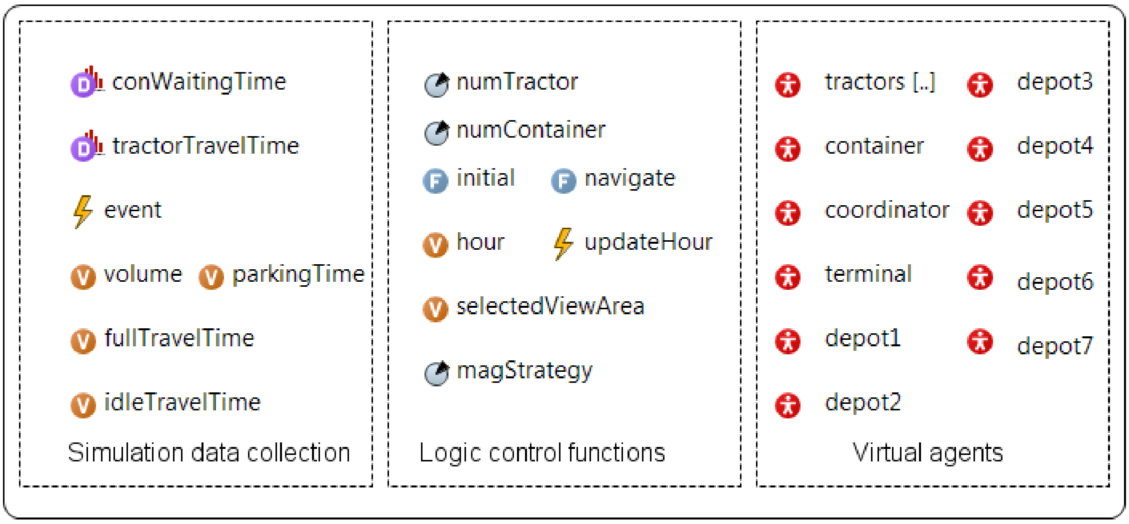

Figure 3. Construction of the simulation model.

4.1 Verification

As explained in the simulation framework, the verification and validation of the model is performed to ensure reliable projections, which form an important part of simulation applications in freight transport. The validation of an agent-based simulation model for future scenarios is particularly challenging for some simulation projects of future systems or imaginary situations, given the scarcity of the data and the difficulty of data acquisition. We have observed the use of customer and expert experience for business verification and validation purposes. As a non-statistical validation technique, participatory simulation has been used to endorse a simulated environment of a city logistics system [26]. In this work, the verification is performed based on the observation of detailed entity flows in the simulator, as Figure 4 shows. Validation is performed in a two-step process.

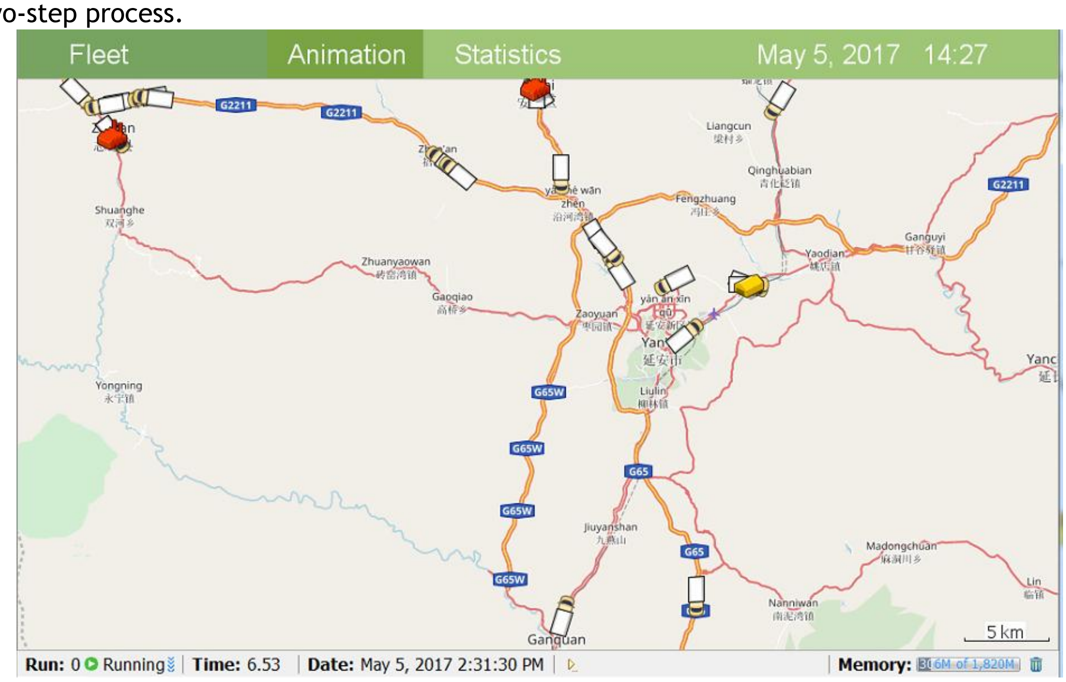

Figure 4. Verification of the simulation ( :Tractor with physical internet container;  :Manufacturing site;  :Freight Terminal).

4.2 Validation

No significant discrepancies were observed with the facility throughputs and the shipment counts. Facility throughputs are the number of containers passing through a node. Figure 5 presents the positioning of the simulation results in confidence intervals. The actual facility throughputs and the daily number of shipments are compared with those of simulation results based on a calculation of 20 randomly seeded iterations. For easy comparison, the throughput is scaled up to an annual amount based on a simulation of 7-day operation, because the annual throughput data are available. A comparison shows that the confidence interval for throughputs and daily shipments are 95% and 90%. These indicate satisfactory accuracy of the simulation model for conducting experiments. The average trailer waiting time is approximately 4 h, and the tractor driving time is 5 h. In addition, fleet utilisations vary between day and night. That is rooted in the management of city logistics. The daytime access regulations in city logistics and congestion do not create a suitable environment for daytime deliveries, which means that night deliveries are widely used by smaller shippers in the context of this use case. The simulation performance is in line with that practice. The data adapter is necessary and important for estimating daily orders. Based on model verification and validation, this agent-based simulation scheme was used for further logistics network configurations, the application of the physical internet with a particular boundary, and infrastructural measurement, such as the necessary expansion of a pre-existing freight terminal to accommodate the increased exchange of production and raw material flows.

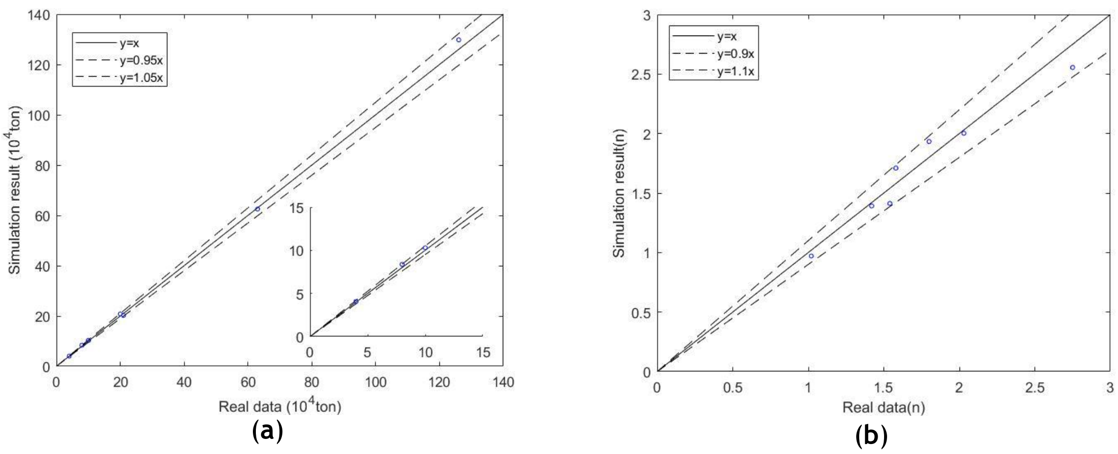

Figure 5. Comparing simulation results with real data (left: facility throughputs; right: average counts of shipments).

5. Results and discussion

5.1 Robustness assessment of the simulation model

An assessment of simulation robustness could be performed to understand the reaction of the model to various impact factors. One example of an impact factor is the tractor sizing. Tractors comprise a large proportion of operational costs, and are therefore an important input for freight system engineering. Because the values of the two variables (the number of tractors and containers) influence each other, we first perform a sensitivity analysis on the system performance corresponding to the tractor fleet sizing. The product storage level represents the parking load at depots. The distribution of physical internet container wait time and tractor travel time indicates the freight efficiency.

After exploring fleet sizing scenarios, it is evident that the number of tractors does affect multiple aspects of the system. We interactively investigated the changes in container waiting times, tractor travel times, and the accumulation of deployed products, as demonstrated by Figure 6. A tractor fleet of 50 will encounter accumulated delayed products and is therefore not sufficient for handling the demands. As long as the tractor fleet increases to 60, a stable exchange of flows and storage of delayed products occurs at all depots, with a maximum storage level at 63. The average container waiting time is 3.16 h, but a few containers waited for more than 10 h. The majority of wait times range from 0–5 h. The tractor travel times are more evenly distributed. The average value is 5.91 h. For the last scenario, a tractor fleet of 70 cannot further reduce the maximum storage of delayed products. However, the container wait time and tractor traveling times are improved. The container wait times are mainly between 0 and 2.5 h, with an average value of 2.58 h. Very few containers wait for more than 10 h. For tractor travel time, nearly 15% travel for less than 1 h. The majority of travel times are between 2.5 and 7 h. The proportion of travel times exceeding 10 h significantly decreases. The government of a logistics network is faced with deep uncertainty. With a focus on all involved actors, a robustness assessment of the simulation model makes complexity manageable.

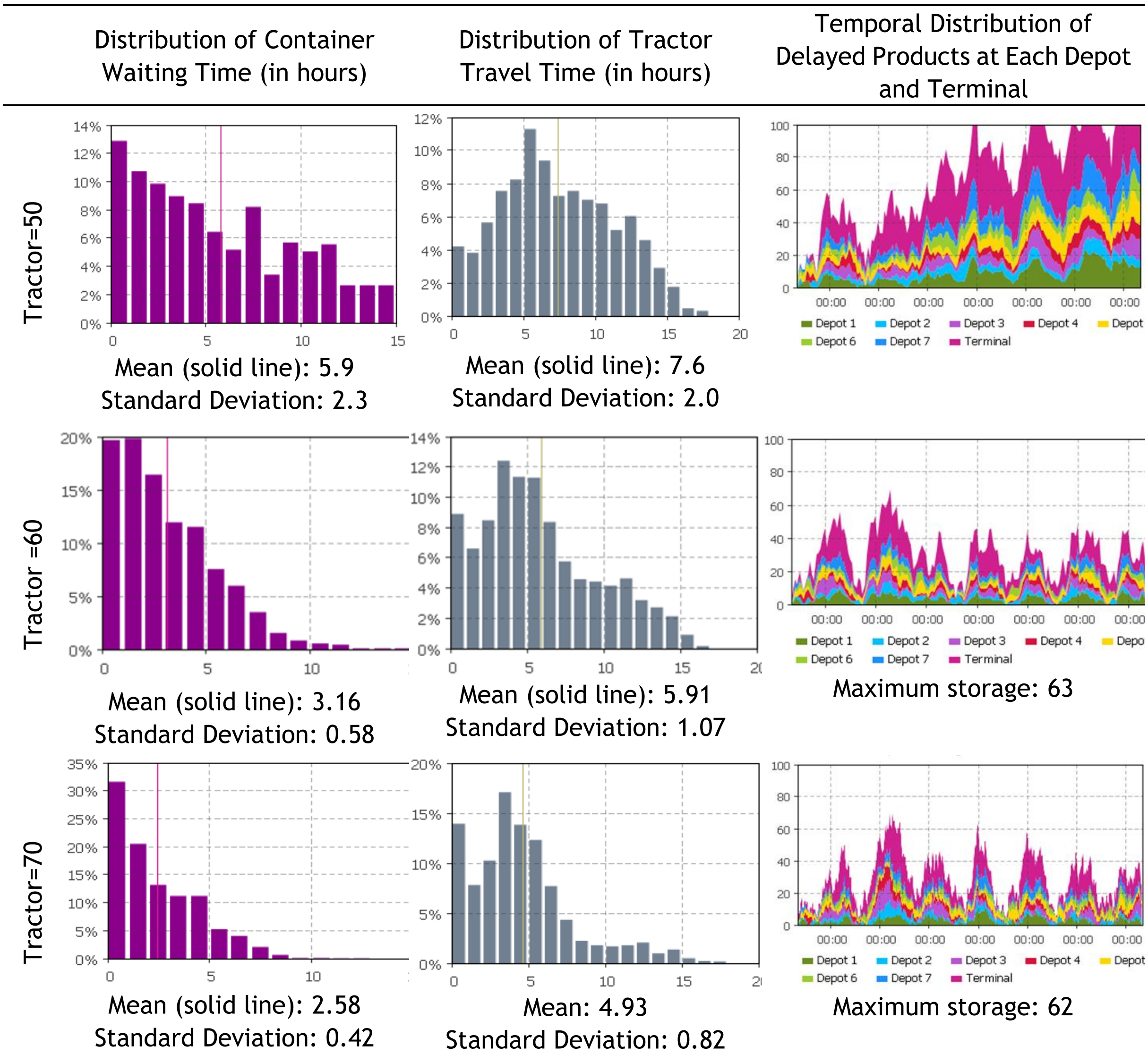

Figure 6. Impact of fleet size options on freight mobility.

5.2 Freight mobility, efficiency, and environmental impacts

The tractor travel time significantly decreases compared with the direct shipments, as Figure 5 shows. Excessive travel times (longer than 10 h) are expected to be reduced because of the physical internet. The change in tractor travel time corresponds to improved in-cab conditions for drivers without sacrificing freight throughput output. The presence of excessively long driving times occurs at a much lower frequency in the new operational model.

A smaller tractor fleet size using the physical internet does not achieve reduced freight throughput or an increased management cost per shipment. Table 2 summarises the number of vehicle kilometres travelled, the fully loaded travel distance, and the environmental impact (CO2 emissions). The presented values are those of daily figures scaled up to the annual figures. The average values are calculated based on 20 iterations with random seeds. The variations become less meaningful in this context because the day to night variation is derived by economic activities. The next paragraphs will compare efficiency, effectiveness, and the societal impacts of the physical-internet-embedded scenario with those of the direct shipment model. The transport cost calculation has accounted for different components such as maintenance, driver retention, and fuel usage. A unified cost rate helps managers to have direct knowledge of the effectiveness of the system.

Economic indicators are computed and compared with previous studies. Studies conducted by Ballot et al. [19], Sarraij et al. [22], and Yang et al. [25] are selected as a basis for conducting benchmark analyses. These works are selected because they also simulate the impacts of the physical internet on the logistics network between the two states of the system, namely physical-internet-enabled and non-physical-internet-enabled. Our results confirm the potential benefits of an open global system. It is expected that the number of vehicle kilometres travelled, and freight throughput will increase with the use of the physical internet. This result is caused by the extension of the logistics network capacity. The capacity increase results from the modular vehicle units that are free of fixed stations and owners. While the shipment volume is expected to increase by over 80%, the operational cost would decrease by only 0.05 ¥ per ton-km. The corresponding decrease in cost is 16%. This is compounded with the inclusion of ordering new tractors and physical internet containers, and their replacements of previous low-efficiency vehicles. However, a cost decrease contributes to the competitiveness of the consortium in a market-based system. The following conclusions can be drawn:

(1) While the payload distance increases significantly, this does not necessarily mean that fuel consumption would increase. This is because loading units are more efficiently utilised compared to direct shipment.

(2) The physical-internet-enabled logistics system utilises less fuel over a given payload distance. With direct shipment, the fuel consumption associated with shipping 100 ton-km is 1.58 L, whereas that of the physical internet is expected to be 1.26 litters. The environmental benefits would support the environmental sustainability in the road haulage portion, which means greener freight can be realised by consortia between road haulage firms.

(3) The annual fuel savings of each tractor for an operation year is 5,633.1 L with a standard deviation of 1,320.24. The fuel savings are mainly achieved by reduced empty driving distance in vehicle kilometres travelled. Fuel savings contribute to economic performance, reduced CO2 emissions, and improved air quality.

7. Discussion and conclusion

Freight transport incorporates many complicated issues, such as network design, fleet management, and route planning. Intermodal transport is a promising innovation model for transitioning road transport to other environmentally friendly modes. The benefits could come from both rail or ocean transport, and could encourage cooperative arrangements under which shippers and carriers can seek improved efficiency. Beneficial situations could be supported by an open, global logistics system with shared responsibility and data accessibility instead of dedicated resources. The prescriptive analytics based on an agent-based simulation include the model development and the scenario design. We attempt to quantify the likely benefits of physical internet in terms of logistical operations.

The physical internet has attracted research attention in recent years. Simulation-based analysis has been rapidly adopted to explore options for how an autonomous environment could be successfully realised in operation, and to show how positive effects may be provisioned at the system level. The effects on transport activities have been identified, including societal, economic, health, and environmental perspectives. Presently, there is a need for innovative simulation models to support distributed logistics systems.

Table 2. Summarized results of efficiency, economic performance and environmental impact.

Operational Model	VKT (10^3* km)	Full Loaded travel distance (10^3*km/ vehicle)	Payload distance (10^3*ton-km/vehicle)	Cost (¥ /ton-km)	Fuel consumption (liter/10^2*ton-km)	Fuel savings (liter/vehicle)
Direct shipment	271.58 (24.44)	230.85 (16.16)	6867.67 (343.38)	0.27 (0.01)	1.58 (0.08)	
Physical internet	396.30 (11.89)	376.48 (11.29)	12518.14 (1126.63)	0.22 (0.01)	1.26 (0.04)	5633.10
Change	45.92%	63.09%	82.28%	-16.13 %	-20.25%	
Ballot et al. [19]	-	-	-	-	-20%	-
Sarraij et al. [22]	-	-	-	-	-60%	-
Yang et al. [25]	-	-	-	-73%	-	-

In this work, an application of the physical internet in a regional logistics network is tested through a simulation-based analysis. The agent-based simulation model is used to evaluate the performance outcomes of collaborative activities. The simulation model is validated based on comparing simulation outputs and real historical data in the pilot case. Although these historical data are in an aggregated format without much detail, we use data adaption for estimating daily flows. Our results confirm the positive impacts of the physical internet and reorganizing the logistics network on freight mobility, efficiency, and external impacts on the environment.

There are not many comparable studies that quantify such a breadth of key performance indicators between two states of a system. The payload distance, an indicator of deadhead movement, is projected to decrease over 80% based on the agent-based simulation. This means that the utilisation of tractors will be much higher in the physical-internet-enabled scenario. The risk associated with this scenario is long working hours for drivers, excessive tractor occupation, and resulting maintenance difficulty. The workload per tractor also increases because of the smaller fleet size and the growth in vehicle-kilometres travelled. The cost and fuel consumption savings are 16% and 20%, respectively. The fuel savings are in line with one previous study; Ballot et al. [19] predicted a similar reduction in fuel consumption (20%). However, Sarraij et al. [22] predicted that the fuel consumption savings would be 60%. Conversely, the logistics cost savings in this work are reasonable because Yang et al. [25] reported that the reduction in logistics cost could be as large as 73%. The relatively larger cost savings achieved in Yang's work are attributed to a more holistic optimisation experiment geared towards reducing operational cost at the system level.

We presented a modular approach to approximate reality in the best possible measure and provide the flexibility of adapting this simulation model in similar logistics networks. The authors also point out the suitability of using agent-based simulation in road haulage for the proper handling of complexity in logistics. The essence of using agent-based simulation is to use detailed operation and the emergence of agent interactions to support strategic planning. Real data are used for scenario generation and simulation validation. This answers the concern that real data were not extensively used in previous simulation assessments of physical internet management systems. Additionally, using simulation-based analysis provides quantitative knowledge on organisational changes and projections of perceived effects. However, there has been a need for validated decision support systems to explore the coordination of the technical components of a logistics system in a physical internet context, and to bring different stakeholders together, especially in developing rural areas with rapid growing freight transport demand.

In this work, we aimed to quantify improvement options in the physical internet in a consortium of shippers and facility owners. We developed interactive tractor and trailer container rules at the most basic level of the system, which was not performed in previous literature. A simulation model is constructed to assess the use of mobile resources and freight operations in an open, global, and distributed logistics network of manufacture sites, shippers, and a single-hub freight terminal. The agent-based simulation model examines the resource utilisations and predicts the impact of physical-internet-enabled logistics operation on costs, facilities, and the environment. We expect this work to provide an agent-based framework that is built on proactive modelling of containers, the interaction of the fundamental operational units of the system, and a comparable study of perceived benefits of the physical internet on addressing logistics sustainability. This study is also expected to enrich literature on freight planning by using an agent-based simulation and its corresponding validation by deploying real-world data.

Limitations do exist and need to be addressed in further studies. Because we only model the freight container at the transport unit layer, the packaging layer with docking for handling less-than-truckload orders is worthwhile to be included in future studies. Detailed information on traffic congestions is difficult for such a large geographical area. Therefore, real-time traffic conditions in city logistics and highways are absent in this study. An alternative could be defining parking-restriction zones and other accessibility regulations imposed on urban transport. A simulation-optimisation experiment could be implemented if certain objectives are to be satisfied, e.g. minimised waiting times for containers or maximised utilisation of vehicles. The robustness of the simulation model could be measured against more assumptions, and the data input can be tested (e.g. assumption on physical impact, parking slot utilisation, rests and inspection durations).

Acknowledgments: This study is supported by the National Social Science Foundation of China under Grant No. 17CGL019. The authors would also like to thank Cyril Bernard Lucas from the United Kingdom, author of the book *Atomic and Molecular Beams: Production and Collimation*, for his great contributions in helping us edit and polish the language of this paper.

Conflicts of Interest: The authors declare no conflict of interest.

Data Availability: The authors declare the data supporting the results reported in a published article can be found.

References

1. Carrara, S.; Thomas, L. Freight Futures: The potential impact of road freight on climate policy. *Transportation Research Part D: Transport and Environment* **2016**, *55*, 359-372. https://doi.org/10.1016/j.trd.2016.10.007
2. Transportation Research Board of the National Academies. The role of freight transportation in economic competitiveness **2014**. http://onlinepubs.trb.org/onlinepubs/conferences/2014/UTCSpotlight/Program.pdf
3. World Economic Forum. Supply Chain Decarbonization. **2009**. http://www3.weforum.org/docs/WEF_LT_SupplyChainDecarbonization_Report_2009.pdf
4. McKinnon, A. Innovation in road freight transport: achievements and challenges. *International Conference on Innovation in Road Transport: Opportunities for Improving Efficiency* **2009**. https://trid.trb.org/view.aspx?id=1149671
5. International Transport Forum. Transport Outlook 2015 **2015** http://www.oecd.org/environment/itf-transport-outlook-2015-9789282107782-en.htm
6. Landschützer, C.; Ehrentraut, F.; Jodin, D. Containers for the Physical Internet: requirements and engineering design related to FMCG logistics. *Logistics Research* **2015**, *8*, 1-22. https://link.springer.com/article/10.1007/s12159-015-0126-3
7. Montreuil, B. Toward a Physical Internet: meeting the global logistics sustainability grand challenge. *Logistics Research* **2011**, *3*, 71-87. https://link.springer.com/article/10.1007/s12159-011-0045-x
8. Colin, J.Y.; Nakechbandi, M.; Mathieu, H. Management of mobile resources in Physical Internet logistic models. *International Conference on Advanced Logistics and Transport* **2015**, 323-6. https://doi.org/10.1109/ICAdLT.2015.7136598
9. Hakami, D. From Network to Web dimension in supply chain management. Doctoral Thesis **2012.**
10. Lin, YH.; Meller, R.; Ellis, KP.; Thomas, LM.; Lombardi, BJ. A decomposition-based approach for the selection of standardized modular containers. *International Journal of Production Research* **2014**, 52, 4660-72. http://www.tandfonline.com/doi/abs/10.1080/00207543.2014.883468
11. Sarraj, R.; Ballot, E.; Pan, S.; Montreuil, B. Analogies between Internet network and logistics service networks: challenges involved in the interconnection. *Journal of Intelligent Manufacturing* **2014**, 25, 1207-19. http://link.springer.com/10.1007/s10845-012-0697-7
12. Montreuil, B; Ballot, E; Tremblay, W. Modular design of physical internet transport, handling and packaging containers. *Progress in Material Handling Research* **2014**. https://hal.univ-lorraine.fr/ENSMP_CGS/hal-01487239v1
13. Monteruil, B; Meller, D.; Ballot, E. Physical internet foundations. *Service orientation in holonic and multi-agent manufacturing control* **2013**, 151-66. https://link.springer.com/chapter/10.1007/978-3-642-35852-4_10
14. Jeffery, M. the information highway gets physical. *Science* **2014**. http://science.sciencemag.org/content/344/6188/1104
15. Sternberg, H.; Norrman, A. The Physical Internet – review, analysis and future research agenda. *International Journal of Physical Distribution & Logistics Management* **2017**, 47, 736-42. http://www.emeraldinsight.com.focus.lib.kth.se/doi/full/10.1108/IJPDLM-12-2016-0353

16. Tako, A.; Robinson, S. The Application of Discrete Event Simulation and System Dynamics in the Logistics and Supply Chain Context. *Decision Support Systems* **2012**, *52*, 802-815. https://doi.org/10.1016/j.dss.2011.11.015
17. Holmgren, J.; Davidsson, P.; Persson, J.; Ramstedt, L. TAPAS: A Multi-Agent Based Model for Simulation of Transport Chains. *Simulation Modelling Practice and Theory* **2012**, *23*, 1–18. https://doi.org/10.1016/j.simpat.2011.12.011
18. Caris, A.; Macharis, C.; Janssens, G.K. Network Analysis of Container Barge Transport in the Port of Antwerp by Means of Simulation. *Journal of Transport Geography* **2011**, *19*, 125–33. https://doi.org/10.1016/j.jtrangeo.2009.12.002
19. Ballot et al, 2012: Physical internet enabled open hub network design for distributed networked operations. *Service orientation in holonic and multi-agent manufacturing control* **2012**, 279–92. https://link.springer.com/chapter/10.1007/978-3-642-27449-7_21?no-access=true
20. Hakami, D.; Montreuil, B.; Sarraj, R.; Ballot, R.; Pan, S. Simulating a physical internet enabled mobility web: the case of mass distribution in France. *9th International Conference on Modeling, Optimization and Simulation* **2012**. https://hal.archives-ouvertes.fr/hal-00728584
21. Furtado, P.; Fakhfakh, R.; Frayret, JM.; Biard, P. Simulation of a Physical Internet Based transportation network. *Proceedings of 2013 International Conference on Industrial Engineering and Systems Management* **2013**. http://ieeexplore.ieee.org/document/6761501/?reload=true&arnumber=6761501
22. Sarraj, R.; Ballot, E.; Pan, S.; Hakimi, D.; Montreuil, B. Interconnected logistic networks and protocols: simulation-based efficiency assessment. *International Journal of Production Research,* **2014**, *52:11*, 3185-208. http://dx.doi.org/10.1080/00207543.2013.865853
23. Pan, S.; Ballot, E. Open Tracing Container Repositioning Simulation Optimization: A Case Study of FMCG Supply Chain. *Service orientation in holonic and multi-agent manufacturing* **2015**, 281–91. http://link.springer.com/10.1007/978-3-319-15159-5_26
24. Pan et al. Perspectives of inventory control models in the Physical Internet: A simulation study. *Computers & Industrial Engineering* **2015**, *84*, 122–32. http://www.sciencedirect.com/science/article/pii/S036083521400415X
25. Yang, Y.; Pan, S.; Ballot, E. Innovative vendor-managed inventory strategy exploiting interconnected logistics services in the Physical Internet. *International Journal of Production Research* **2017**, *55*, 2685–702. https://www.tandfonline.com/doi/full/10.1080/00207543.2016.1275871
26. Anand, N.; Meijer, D.; Vuin, J.; Tavasszy, L.; Meijer, S. Validation of an Agent Based Model Using a Participatory Simulation Gaming Approach: the Case of City Logistics. *Transportation Research Part C: Emerging Technologies* **2016**, 71, 489-99. https://doi.org/10.1016/j.trc.2016.08.002
27. Caris, A.; Macharis, C.; Janssens, G.K. Network Analysis of Container Barge Transport in the Port of Antwerp by Means of Simulation. *Journal of Transport Geography* **2011**, *19*, 125–33. https://doi.org/10.1016/j.jtrangeo.2009.12.002
28. Davidsson, P.; Henesey, L.; Ramstedt, L.; Törnquist, J.; Wernstedt, F. An Analysis of Agent-Based Approaches to Transport Logistics. *Transportation Research Part C: Emerging Technologies* **2005**, *13*, 255-71. https://doi.org/10.1016/j.trc.2005.07.002
29. Banks, J.; Chwif, L. Warnings about Simulation. *Journal of Simulation* **2011**, *5*, 279–291. https://link.springer.com/article/10.1057/jos.2010.24
30. Hakimi, D.; Montreuil, B.; Labarthe, O.; Retail Store Demand Estimation for Supply Network Simulation. *8th International Conference of Modeling and Simulation* **2010**. http://www.enim.fr/mosim2010/articles/361.pdf
31. Sun, Y.; Lang, M., Modeling the Multicommodity Multimodal Routing Problem with Schedule-Based Services and Carbon Dioxide Emission Cost. *Mathematical Problems in Engineering* **2015**, *2015*, 1-21. http://dx.doi.org/10.1155/2015/406218