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Multiagent Modelling and Simulation of a Physical Internet Enabled Rail-Road Intermodal Transport System

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Abstract Simulation-based analysis has been used for planning, control, and decision-making support of physical internet enabled logistics networks. However, multiagent modelling and simulation based on micro-level interactions have been rarely developed for the pre-studies of digital transformation of urban rail transit systems. This hinders a wider industrial deployment of agent technology in the physical internet enabled transport infrastructure. To fill in this knowledge gap, this work presents an agent-based simulation that explicitly models the micro-level protocols of mobile recourse units and their interaction with the physical infrastructure in a rail-road intermodal transport network. Parameterisation of the simulation model is changeable to examine the influences of different efficiency factors. This allows understanding of which structural functions and resource configuration would make an impact system-wide. Through a practical application, a multiagent system is developed for modelling and analysis of sustainable logistics with individually operated mobile resource units. An agent-based simulation assessment is performed to quantify the improvement options. The results reveal that the physical internet can prevent trucks from empty driving, which has a positive effect on the sustainable logistics operations. The proposed model can be used to support the deployment and planning of digital transformation that could be implemented in urban rail transit systems serving urban distribution and passenger transport.

Keywords Agent-based simulation · Rail-road intermodal transport · Physical internet

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1 Introduction

1.1 Intermodal Transport Systems

Rail-road intermodal transport is critical for urban concentrations and exerts an influence on many essential aspects of the 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 by shifting the volumes to environment-friendly options, like rail and ocean transport [2]. Mobility affects both transit users and freight with regards to the timely, efficient provision of service, and further connects the competitiveness of products, especially in sectors with low-margin profits and stochastic demands. Nowadays transit systems are extending its functionality. Terminals are in the process of integrating road transport for the delivery of goods and parcels.

Road freight transport is an enabler green house logistics operation because it is the biggest greenhouse gas emission generator of all transport modes [3]. Therefore, the road freight transport shows a potential for achieving resource and environmental efficiencies for addressing the sustainability challenge. Meanwhile, the financial status of supply chain operators relies on the transport operation. These dimensions could be realised by innovations, with the physical internet as a concrete example of digital transformation of service. Logistics innovations are encouraged in road freight transport because they enable improvements in trucking productivity, emission reduction, and in-cab conditions (e.g. health and safety) [4].

The penetration of seamless intermodal transport is evidenced in the urban transport context. With urban rail transit systems aimed for regional mobility and accessibility, rail-road intermodal terminals are nowadays serving traffic flows of multiple sources. These sources include urban distribution and passenger transport. The physical flows are utilising shared infrastructure space and make the planning of terminal and network an important part of management. For strategic planning of urban rail transit systems, Sharav et al. used graph theory and performance measurements for comparing the alternatives of transit network design [5]. Through spatial data analysis, Aklilu and Necha assessed the accessibility of public transport with the particular aspects of service area coverage and the quantification of transit users [6]. A queue model was developed for optimisation of walkways, a facility design issue inside the transit terminal [7]. Tang and Hu developed an agent-based model for understanding pedestrian dynamics and interactions in the public space, and the associated transition from micro-level organisations to the global phenomena [8] that might be critical for the infrastructure. The model projected the crowd flow, total travel time, density, and public accessibility that support facility design of transit terminals.

In global operations, intermodal transport facilitates collaborative delivery across modes in freight transport. According to the forecasts, the throughput of intermodal transport 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 transport will increase fourfold until 2050 [9]. One of the main operation technologies driving the development of intermodal transport is the ‘drop and pull’ or swap-body service shown in Fig. 1. 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 transport and has developed into a model across different transport means and modals.

The standardisation of transport units (e.g. modular containers) provides many opportunities to integrate the transport systems. It motivates haulage firms to exchange flows and improve freight mobility to ship goods in large-scale distribution [10]. 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 transhipped from road transport to rail or ocean transport, which possess better sustainability and reduce greenhouse emissions. The improvements to efficiency and environmental impact that can be achieved by adopting a modular design of a material handling system are of interest to both freight and service providers.

1.2 Physical Internet in the Logistics Sector

The efficient transport 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 transport industry, the physical internet, an innovative concept first introduced by 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 [11], rather than dedicated and specialised networks. The physical internet enables logistics networks to encapsulate goods in modular vehicle units. The standardised mobile resources in the physical internet will be mutually managed by several shippers instead of individual managers [12]. For a sustainable operation, supply chain interoperability, economic, environmental, and societal efficiency are important research highlights in the literature.

Previous studies emphasized the foundations of the physical internet by physical, digital, and operational interconnectivity through encapsulations, interfaces, and protocols as a solution for logistics sustainability challenges [13–17]. These studies identified opportunities to integrate the physical internet in the logistics sector to improve the three dimensions of sustainable operations through the technological or business model innovation. An article by Science Magazine [18] stated that the physical internet will move goods much in the same way as its

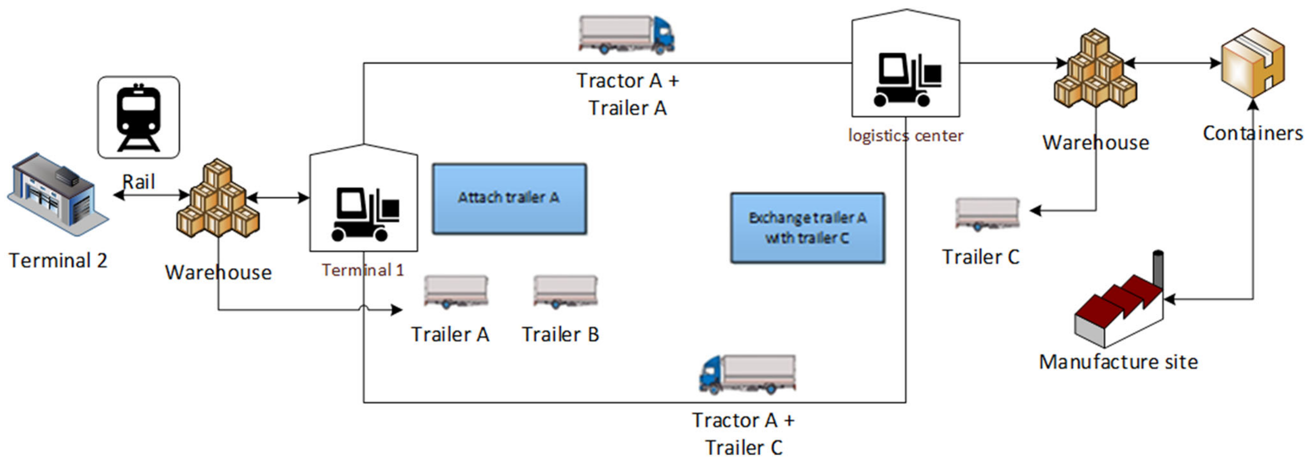

Fig. 1 Containerisation of goods

digital namesake moves data, and promote collaboration in developing standardised containers, common protocols, and tools. Various simulation and optimisation methods for the engineering design of the physical internet were reported in previous studies. A literature review concluded that 46 applications have been performed and the applied methods are generally diversified [19].

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 [20] 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 such technologies in the governance and planning of complex logistics systems. Holmgren et al. [21] constructed a Transport 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 were achieved by shifting goods from road transport to rail and ocean transport. Caris et al. [22] addressed different cases of port locations and their impacts on network characteristics.

Several recent simulation studies analysed the different 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. [23] presented an evolutionary 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 reforming the organisation of transport. Hakami et al. [24] 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 revealed the structural impacts, e.g. increased number of delivery trips. The efficiency of transport was realised by the significant reduction in the total travel distance. They pointed out that the physical internet profoundly rendered the way physical objects are transported. Furtado et al. [25] modelled the transport 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 [26], container repositioning strategy [27], and inventory controls [28, 29].

Above all others, agent-based simulation is best suitable for modelling detailed operations in many sectors (e.g. city logistics [30], production systems [31], and marine logistics [32]) because it is the only simulation paradigm that supports prescriptive analytics based on the interactions between elements. 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 multiagent frameworks that conceptualise the interactions between tractors and trailer containers in a digitally transformed service network. Very few simulation studies assign decentralised capacity to make containers objective-oriented rather than being 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 during the digital transformation.

This paper examines the performance indicator changes based on the multiagent simulation before and after the implementation of the physical internet in an urban rail transit system. Considering that the digital transformation is targeting the logistics sustainability grand challenge [11], it is important to understand how the urban transit systems benefit from adopting the distributed infrastructure with the help of physical internet and how this could increase the accessibility and mobility of local operators. The investigation is therefore challenged to build validated multiagent simulation for the analysis of infrastructure-meditated impacts on economic and productivity prospects. In contrast to previous works of modelling business processes in transit terminals, this article looks into the distributed operation between resource units supported by real operational data. The simulation model is built upon the flow of multiple types of resources with heterogeneity, allowing for the analysis of the impact of different infrastructure measurements before and after a digital transformation. The schematic of the agent-based simulation intends to be a theoretical framework of developing the micro-level protocols of interacting resource units, whereas the empirical validation is performed for further quantification of improvement options to the rail-road intermodal transport system.

Instead of traditional trucking operations, we suggest that an open global logistics system supported by the physical internet might be a valuable option to consider for system savings of cost and improved social efficiency. This system is developed based on three prerequisites: (1) the abolishment of dedicated infrastructures, (2) the automotive distribution of orders, and (3) real-time control of mobile resource units. Key performance indexes are calculated. The multiagent framework is designed in an object-oriented manner, with the focus on the interactive rules of resource components and the modelling of the active trailer container agents. Similar to previous simulation studies, this work relies on data from freight operations to perform a validation of the multiagent model for the sake of a reliable pre-study. The simulation is programmed for providing realistic views of the network at the model run time.

2 Multiagent-Based Simulation Framework of Freight Transport in Physical Internet

Studies related to complex systems use simulation methods to address the various business models, the cooperative structures, to evaluate potential scenarios with the presence of uncertainty and dynamics. Regarding the context, the intermodal transport organisation is based on the modular design concept but 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 and justify a multiagent architecture suitable for solving the provision of infrastructure.

The logistics system is a complex technical system that can be supported by a modular design [17]. Because agent-based simulation models can help us to understand the behaviour of decentralised freight systems [32], it is considered suitable and useful to construct such a decision support tool based on this 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 fully utilises a modular approach to model the interaction of mobile resource units and their effect on freight performance. This section presents the multiagent framework for recreating interactive rules of different actors. Agent-based simulation is used for quantifying the improvement options made possible by the physical internet. Relationships across agents are shown in Fig. 2.

Three transport operation elements are modelled by four different types of agents: depot, coordinator, tractors, and containers. Within the physical entity simulator, these are populations of agents depending on the size of each resource pool. The physical entity simulator is based on an open-source geographical information system, OpenStreetMap, which is the spatial representation for synchronising transport-related measurements. The transport-related indicators are updated when delivery orders enter or sink. The agents' behaviours overtime are presented to the user of the model for his better understanding of causality and effects of the efficiency factors. To this end, those agents, all of which are independently functioning, are used to model the movement of goods and mobile resources for the multiple-site physical distributions. The tractors, coordinator, and containers are active agents for operational control, whereas the depot is a passive agent that acts as an infrastructure node.

1. The depot is a population of nodes that represent a rail-road freight terminal and smaller depots connected by road haulages. Nevertheless, all depots share common

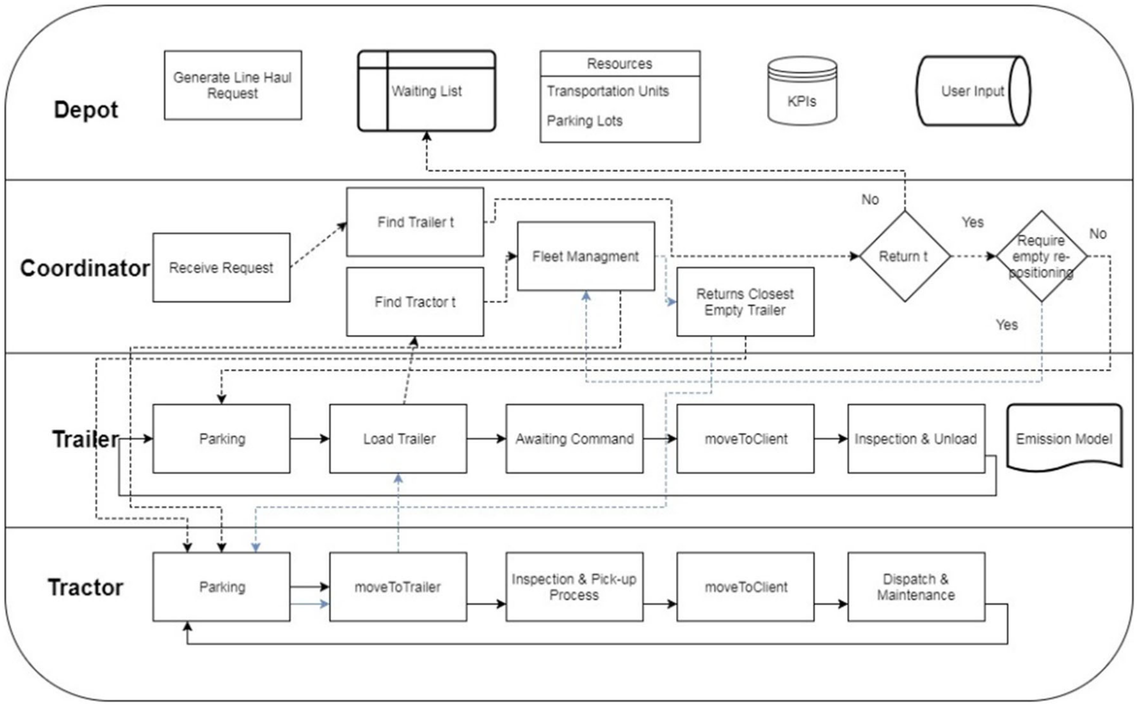

Fig. 2 Schematic of the agent-based simulation framework

attributes, including the generation of freight transport demand, waiting lists, resource pools, and the calculation of key performance indicators, the ones widely used in the system analysis of logistics performance. Scenario generation is controlled by a dynamic event. Historical orders are disaggregated by the data adaptor. 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 visible 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. As mentioned in classic operations, tractors and containers are the message receivers of production and transport orders and react according to the specific type of order and transport proposal delivered by the coordinator. The tractors and trailers are also managed centrally. 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 protocols 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 to the intermodal terminal. Products will then be gathered at the terminal for railway transport.
3. The coordinator is a single 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 workflows 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 above-mentioned 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 are prepared for the next mission, and the tractor might head towards a

specific location. If containers are starved at a hub, the coordinator might 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 rather than a centralised delegation.

Logistics operations for uploading, delivery, parking, and exchange are explicitly modelled for handling inbound and outbound orders. These machine states characterise the essentials of the investigated system. 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 will eventually determine the economic and environmental sustainability at the system level. The handling of containers is triggered when a delivery request message is received.

By doing so, we modelled individual decision-making processes at three levels: the network level, the terminal level, and the vehicular unit level. Using agents are intended to represent the real-world decision-making in management control, facility operations, and transport processes. We have followed the suggestion of model construction proposed by Banks and Chwif [33], that is, constructing a model of sufficient level (not too simple, not too complex), conducting the conceptualisation prior to simulation implementation, and validating the computational model gradually. At the network level, management controls address real-time fleet assignments to reduce container waiting times. At the depot and terminal level, facility operations include the interaction of the temporary storage of delayed products, physical internet containers, departures of trucks, and freight trains. The tractors and containers are modelled as agents interacting not only with each other and but as well with the spatial continuous environment. These modelling perspectives are aimed to approximate reality and increase the confidence and reliability of the model-based analysis. 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.

Real freight and structural data are provided by a regional consortium of shippers and intermodal facility owners. 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 used for the data generation function of the simulation model. 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.

3 Case Study: Simulation and Validation

This section presents the context and background of the investigated urban transit system, its simulation model construction, and validation. The original infrastructure plan for the practical application is a horizontal integration of upstream and downstream operations to pursue regional competitiveness of 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 planning of freight terminals served by rail and road links. The freight terminal functions as a single hub for all outbound and inbound flows and connects upstream shippers. The road-based freight transport needs to eliminate congestion, delivery delays, and inefficient utilisation of tractors and trailers. In this sense, the utilisation of digital transformation might be an advantage since traffic congestion management could be supported by physical internet technology [34]. Spatially, the road haulage firms, with their own hubs, are located in fronts of the urban concentration, whereas the facility operator is located at the suburban area of the city. For the physical internet scenario, we consider the option of using physical internet infrastructure 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. Data are available from August 2014 to July 2015 and include shipments per tractor, total payload distance, and other operational details. Freight flows are disaggregated into daily delivery orders using a data adapter proposed by Hakimi et al. [34].

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 an emission factor [35]. Operation cost is a global indicator composed of many components in the process of handling containers. For presentation convenience, the Yuan (¥) currency is used for costs. Indicators, formulations, and units are presented in Table 2.

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	$\Sigma_t D_t, D_t$: travel distance of tractor t. unit: km
Full loaded travel distance	$\Sigma_t \frac{D_{t-\text{load}}}{N_t}$, $D_{t-\text{load}}$: loaded travel distance of tractor t; N_t: number of tractors. unit: km/vehicle
Payload distance	$\Sigma_t \frac{D_{t-\text{load}} \times t_{\text{load}}}{N_t}$, t_{load} : weight of tractor. unit: ton-km/vehicle
Fuel consumption	$\Sigma_t O_t / (\Sigma_t D_{t-\text{load}} \times t_{\text{load}})$, O_t: oil consumption of tractor t. unit: L/ton-km
Logistics cost	$\Sigma_t O_t \times 6.90 + N_t \times 24000 + N_c \times 2 \times 48000 + \Sigma_t D_{t-\text{load}} \times t_{\text{load}} * 0.06)/(\Sigma_t D_{t-\text{load}} \times t_{\text{load}})$, N_c: number of containers. unit: ¥/ton-km

3.1 Simulation

The agent-based simulation framework was configured to construct the simulation and is presented in Fig. 3. For each type of agent, the internal decision-making process was programmed in AnyLogic. 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.

3.2 Verification

As explained in the simulation framework, the verification and validation of the model are performed to ensure reliable projections, an important part of simulation-based analysis in freight transport. The validation of models for future scenarios is particularly challenging for simulations 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 an example of the non-statistical validation technique, participatory simulation has been used to endorse a simulated environment of a city logistics system [30]. In this work, the verification is performed based on the observation of detailed entity flows in the simulator, as Fig. 4 shows.

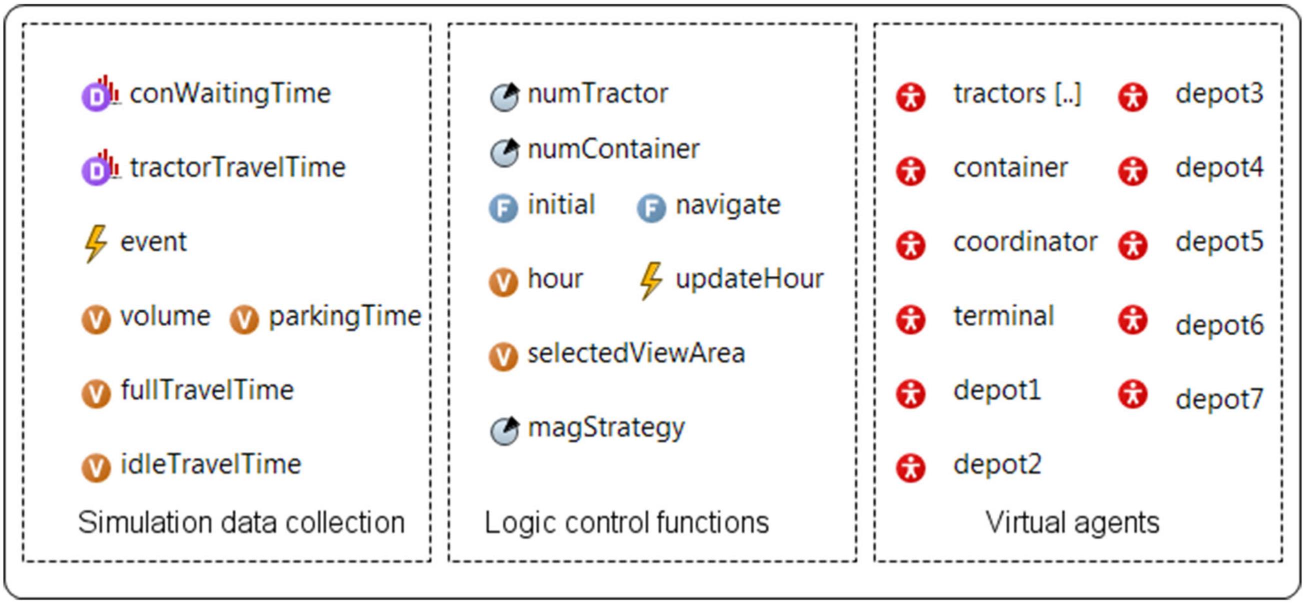

Fig. 3 Construction of the simulation model

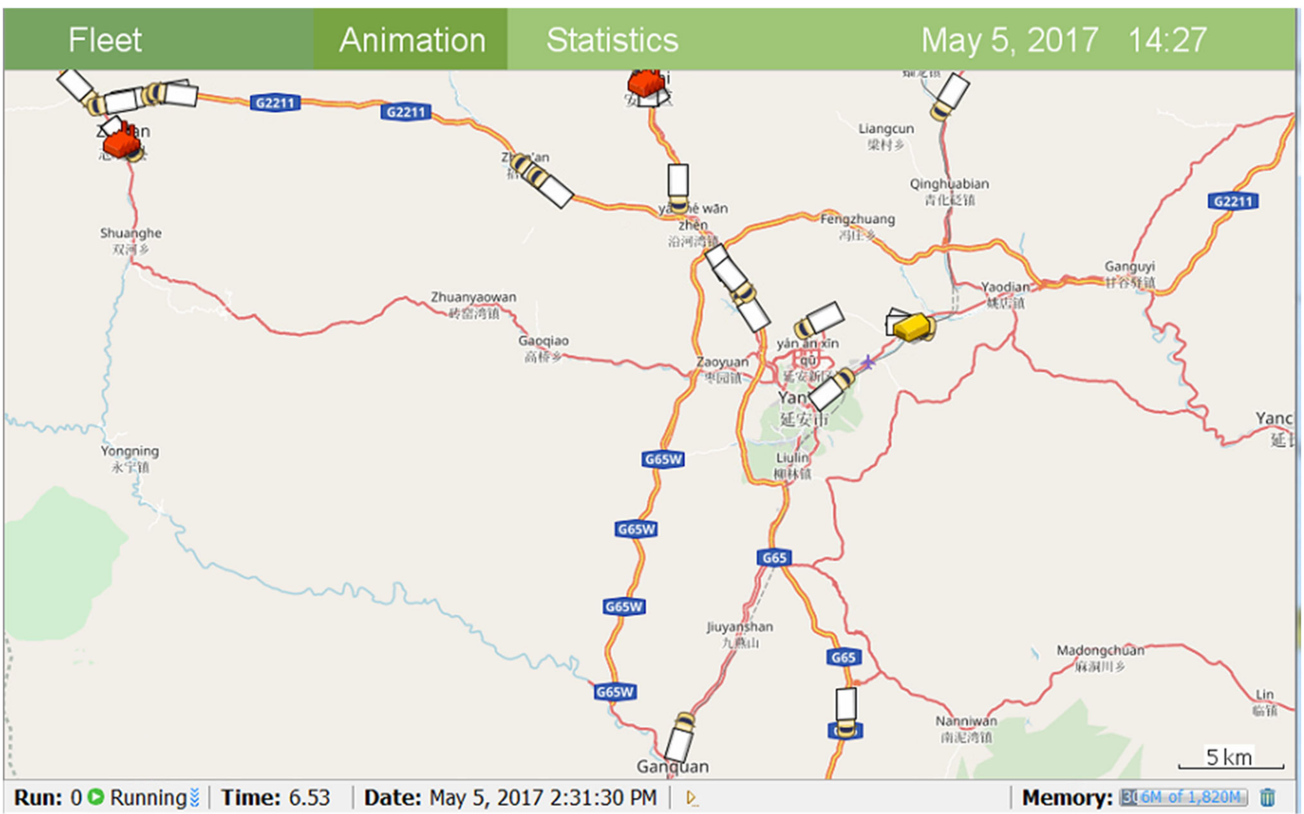

Fig. 4 Verification of the simulation (: tractor with physical internet container; : manufacturing site; : freight terminal)

3.3 Validation

No significant discrepancies were observed with the facility throughputs and the shipment counts. Facility throughputs are the number of containers passing through a rail-road intermodal terminal. Figure 5 presents the positioning of the simulation results in confidence intervals. The actual facility throughputs and the daily number of

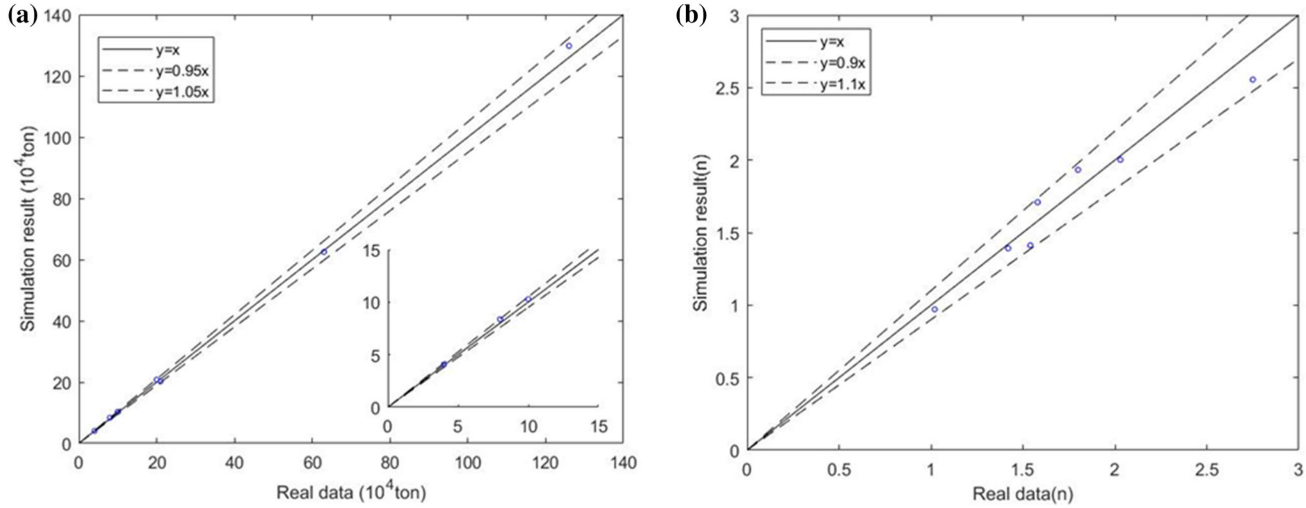

Fig. 5 Comparing simulation results with real data (left: facility throughputs; right: average counts of shipments)

Table 3 Summarised results of efficiency, economic performance, and environmental impact

Operational Model	VKT ($10^3 \times$ km)	Full loaded travel distance ($10^3 \times$ km/vehicle)	Payload distance ($10^3 \times$ ton-km/vehicle)	Cost (¥/ton-km)	Fuel consumption (litre/$10^2 \times$ ton-km)	Fuel savings (litre/vehicle)
Direct shipment	271.58 (24.44)	230.85 (16.16)	6867.67 (343.38)	0.27 (0.01)	1.58 (0.08)	5633.10
Physical Internet	396.30 (11.89)	376.48 (11.29)	12518.14 (1126.63)	0.22 (0.01)	1.26 (0.04)	
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%	–	–

shipments are compared with those of simulation results based on a calculation of 20 unique iterations. For easy comparison, the throughput is scaled up to an annual amount based on a simulation of a 7-day operation, because the annual throughput data are an available source. A comparison shows that the confidence interval for throughputs and daily shipments is 95 and 90%. These indicate a 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. The reason of that is rooted in the regulation of urban logistics. The daytime access regulations in urban physical distribution do not create a suitable environment for daytime deliveries, which means that night deliveries are widely adopted 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 able to be 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 preexisting freight terminal to accommodate the exchange of production and raw material flows.

4 Result and Discussion

4.1 Robustness Assessment of the Simulation Model

An assessment of simulation robustness could be performed to understand the sensitivity of the model to various impact factors. One example of an efficiency factor is the tractor sizing. Tractors comprise a large proportion of operational costs and are therefore the focal point for freight system engineering in many business cases. 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 waiting time and tractor travel time would indicate the freight efficiency.

As mentioned, this simulation model can interact with the stakeholder for better understanding of desired situations. One of the concerns of the shipper is fleet sizing. The supply chain operators are willing to retain a limited number of expensive assets for the sake of a healthy financial status. The user can change parameterisation of the simulation model, play back the simulation run, and present specific points of view of simulated reality. The simulation model can interface with optimisation algorithms for designing terminals and flows. This interface with external application will be the further direction of this work.

By manipulating the parameters directly, the user is easy to identify that the number of tractors does affect multiple dimensions and perspectives of the system, and investigate the changes in container waiting times, tractor travel times, and the accumulation of deployed products, as demonstrated in Fig. 5. 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 waiting times range from 0 to 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 waiting time and tractor travelling times are improved. The container waiting 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 above interaction of the model and the user would demonstrate that the management of a logistics network is faced with uncertainty and dynamics that are difficult to capture beforehand. A robustness assessment of the simulation model makes this complexity manageable.

4.2 Freight Mobility, Efficiency, and Environmental Impacts

The tractor travel time significantly decreases in the physical internet scenario compared with the baseline scenario, as Fig. 6 shows. Excessive travel times (longer than 10 h) are expected to reduce because of the circulation of resources. The change in tractor travel time corresponds to improved in-cab conditions for drivers without compromising freight throughput output. The presence of excessively long driving times occurs at a much lower frequency in this new operational model.

A smaller tractor fleet size using the physical internet does not result lower freight throughput or an increased management cost per shipment. Table 3 summarises the number of vehicle kilometres travelled, the fully loaded travel distance, and the environmental impact (CO_2 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 baseline scenario. 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. [23], Sarraij et al. [26], and Yang et al. [29] are selected as a basis for conducting benchmark analyses. These works are identified because they also simulate the impacts of the physical internet on the logistics network based on scenario simulations, 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 benefits from 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. All in all, 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 with the baseline scenario.
2. The physical internet enabled logistics system utilises less fuel over a given payload distance. With the baseline scenario, 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 L. The environmental benefits would support the environmental sustainability in the road haulage portion, which

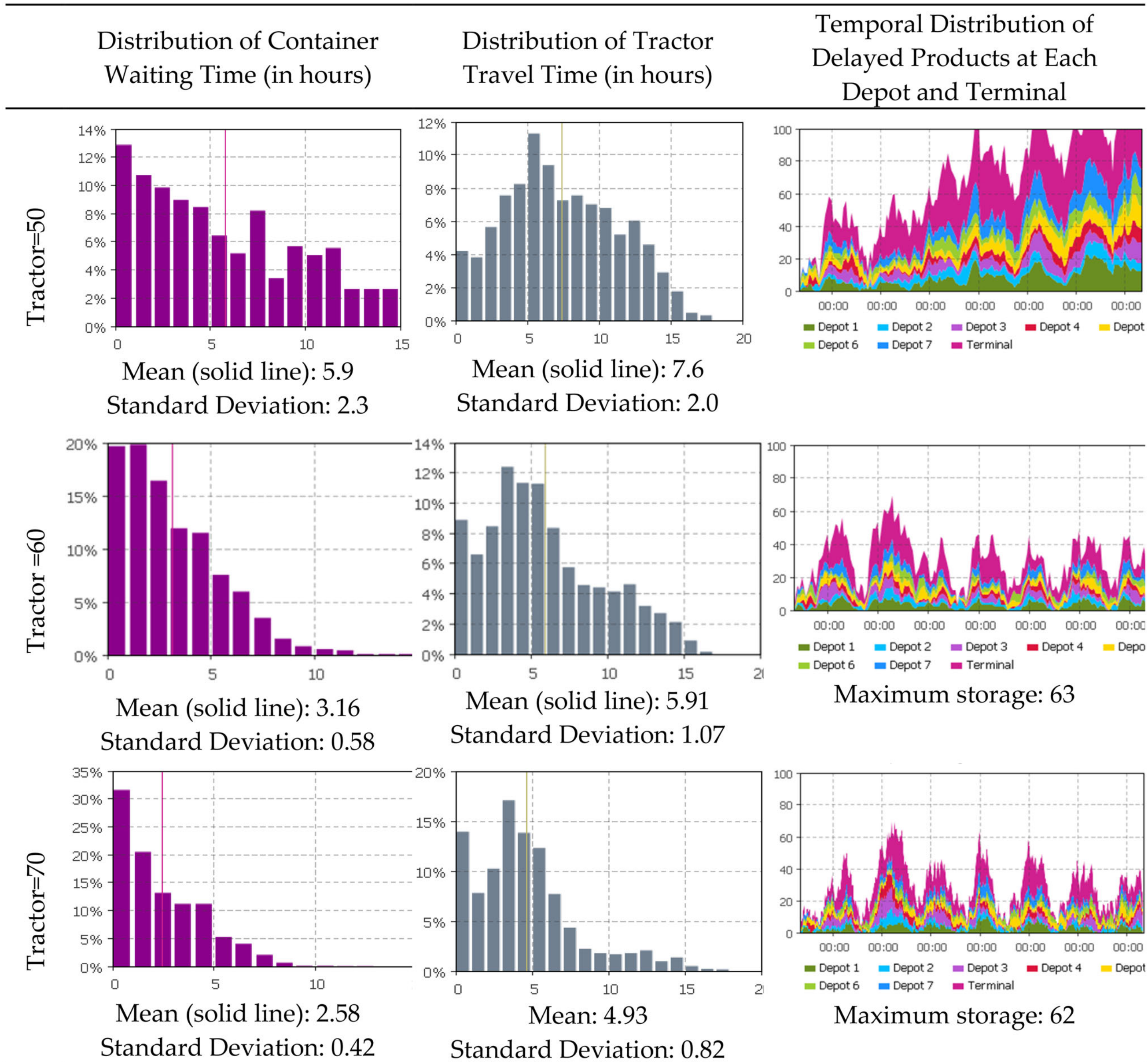

Fig. 6 Impact of fleet size options on freight mobility

means greener freight can be realised by consortia between road haulage firms.

3. The annual fuel savings of each tractor for an operation year are 5633.1 L with a standard deviation of 1320.24. The fuel savings are mainly achieved by reduced empty driving distance in vehicle kilometres travelled. Fuel savings contribute to economic performance, reduced CO_2 emissions, and improved air quality.

5 Discussion and Conclusion

Freight transport incorporates many complicated issues, such as network design, fleet management, and route planning. Intermodal transport will play a major role of urban logistics and passenger transport for the sustainable operations. The benefits could come from either 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. In this work, transformation into a physical internet enabled scenario is applied on an urban rail transit system. The prescriptive analytics based on an agent-based simulation help solve the provision of infrastructure. We attempt to quantify the likely benefits of physical internet on 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.

An application of the physical internet in a regional logistics network is tested through a simulation-based prestudy. 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 reorganising the logistics network on freight mobility, efficiency, and external impacts on the environment.

Presently, there are not many comparable studies that quantify such a breadth of key performance indicators during the operation phase. 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. [23] predicted a similar reduction in fuel consumption (20%). However, Sarraij et al. [26] predicted that the fuel consumption savings would be 60%. Conversely, the logistics cost savings in this work are reasonable because Yang et al. [29] 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 holistic optimisation experiment geared towards reducing global operational cost.

We presented a modular modelling and simulation approach to approximate the real-world operative environment 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.

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.

We are exploring the specifications of physical internet. 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, detailed traffic conditions with spatial–temporal diversities are not recreated in the simulation. 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).

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Authors' Contribution Chen Zhang proposed the topic discussed in this study and designed the methodology with Yan Sun. Chen Zhang conducted the experiment. Chen Zhang and Yan Sun wrote the manuscript. Kunxiang Dong and Maoxiang Lang thoroughly reviewed the paper and provided constructive suggestions on design, data collection, and interpretation of findings. All authors have discussed and contributed to the manuscript. All authors have read and approved the final manuscript.

Compliance with Ethical Standards

Conflicts of interest The authors declare that they have no conflict of interest.

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