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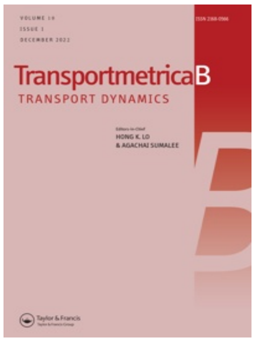

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Evaluating the impact of horizontal collaboration in logistics systems: a simulation-based study

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ABSTRACT

Horizontal collaboration is a critical issue in logistics networks to improve efficiency and sustainability. However, implementing collaborative systems faces significant challenges such as the lack of trust among potential participants and fear of losing competitiveness. To address this challenge, we propose a simulation model of a logistics network that assesses the impact of horizontal collaboration on individual Logistics Service Providers. Our results show that while collaboration generates benefits for the system as a whole, these gains are not evenly distributed among all players, and some may even face losses in certain situations. Our proposed model helps visualise these disparities and can be used to design compensation schemes that encourage Logistics Service Providers to participate in collaborative systems. Overall, the proposed model provides insights into the benefits and challenges of horizontal collaboration in logistics networks, and can be useful for designing more equitable and sustainable logistics systems.

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KEYWORDS
Multimodal freight transport; collaborative logistics; horizontal collaboration; agent-based simulation

1. Introduction

In today's globalised world, efficient transportation and logistics networks play a crucial role in facilitating the movement of goods and services. With the increasing complexity of supply chains and the growing demand for sustainable transport solutions, it becomes imperative to explore innovative strategies that optimise the utilisation of available resources. In this context, novel concepts such as the Physical Internet and Synchromodal transport have emerged, sharing common aspects such as enhanced flexibility and collaboration among various stakeholders. These concepts aim to increase the efficiency of logistics operations, resulting in reduced economic costs, as well as environmental and social externalities. However, despite the proposed benefits of these concepts, several challenges hinder their practical implementation, necessitating further research to bring them into reality.

Collaboration plays a crucial role in logistics operations, enabling organisations to streamline their operations, enhance efficiency, and achieve competitive advantages. In logistics, collaboration refers to the strategic alignment and cooperative efforts among various stakeholders involved in the supply chain network. This collaborative approach facilitates the sharing of information, resources, and responsibilities to optimise the flow of goods and services (Abideen et al. 2023; Aloui et al. 2021; Chen et al. 2017; Pan et al. 2019). There are three primary types of collaboration in logistics: vertical, horizontal, and lateral. Vertical collaboration involves coordination and partnerships across different levels

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of the supply chain, fostering integration and communication between manufacturers, suppliers, distributors, and retailers. Horizontal collaboration focuses on cooperation among entities operating at the same supply chain stage, aiming to achieve economies of scale and reduce costs through resource pooling and consolidation. Lateral collaboration entails partnerships between companies in different industries or sectors, promoting knowledge exchange and resource sharing for improved customer value and operational efficiency. These three types of collaboration, vertical, horizontal, and lateral, are instrumental in enhancing supply chain performance, driving innovation, and establishing a competitive edge in logistics (Aloui et al. 2021; Vargas, Patel, and Patel 2018).

Horizontal collaboration is widely regarded as a key aspect in the future of logistics. This collaboration can occur at various planning horizons, including strategic, tactical, and operational levels. At the strategic level, organisations may engage in collaborative initiatives such as shared distribution centers or joint transport networks, enabling them to optimise their resources and reduce costs. At the tactical and operational levels, collaboration between Logistics Service Providers (LSPs) becomes crucial during transport planning. LSPs can pool their resources, share information, and jointly plan routes and schedules, leading to improved efficiency and reduced empty miles. Such collaboration allows LSPs to leverage each other's capabilities and assets, ultimately enhancing service levels and reducing overall transport costs. By working together during operational transport planning, LSPs can synchronise their operations, share real-time information, and coordinate activities such as delivery sequencing and cross-docking. This results in optimised transport execution and improved customer service. Horizontal collaboration among LSPs enables them to overcome individual limitations and achieve higher levels of efficiency and competitiveness in the dynamic logistics landscape. However, despite its potential benefits, horizontal collaboration in logistics faces several challenges that have hindered its widespread adoption, such as a lack of trust and standardisation, among others. Overcoming these challenges requires additional research and development to explore innovative solutions, develop best practices, and design frameworks that foster effective collaboration. By addressing these challenges, the logistics industry can unlock the full potential of horizontal collaboration and reap its numerous benefits.

Operations research (OR) serves as a valuable tool to promote horizontal collaboration in logistics. It aids in optimising operations and addressing the additional planning requirements that arise from collaboration. By leveraging OR techniques, such as mathematical modelling and optimisation algorithms, stakeholders can determine the most efficient allocation of resources, optimise routes and schedules, and enhance overall supply chain performance. Additionally, OR plays a crucial role in simulating future scenarios, allowing stakeholders to estimate the potential impacts of collaboration on various performance indicators. This capability enables informed decision-making and the identification of strategies that maximise the benefits of horizontal collaboration. Therefore, OR serves as a powerful instrument for driving effective collaboration and realising its potential in the logistics industry.

This paper presents an agent-based simulation model that represents a multimodal logistics network situated in the concept of synchromodality, although it can also be used to model more conventional operations. The model contributes by focusing on aspects relevant to innovative logistics operations, such as flexible and dynamic decision-making. It also benefits from agent-based simulation techniques to represent complex interactions between different stakeholders, particularly LSPs, allowing for the identification of emergent behaviours resulting from these interactions. The focus of this paper is to test the model as a tool to estimate the impact of collaboration in the logistics network, emphasising the impact on individual LSPs to identify winners and losers in the proposed scenarios.

The remainder of this paper is structured as follows: Section 2 presents a literature review on horizontal collaboration in logistics and the use of modelling techniques in this area. Section 3 provides a detailed description of the proposed model and the characteristics of the situation it represents. Section 4 discusses the experimental set-up and presents the main results obtained from the simulation. Finally, Section 5 presents the main conclusions drawn from the study and outlines potential future research directions.

2. Literature review

In this section, we provide a concise review of the literature related to our work, with a specific focus on the utilisation of collaboration to enhance supply chain networks and the application of OR, particularly simulation, in studying and optimising related problems. Through this review, we aim to establish a foundation for our proposed agent-based simulation model and position our research in the state-of-the-art, contributing to the ongoing advancements in collaboration and OR in the logistics domain.

2.1. Collaboration in logistics

Collaboration has emerged as a critical strategy for enhancing efficiency and resilience within logistics and supply chain networks, therefore attracting the interest of researchers. Several benefits have been identified for organisations operating within complex supply chain networks. First and foremost, collaboration enhances operational efficiency by optimising processes, reducing lead times, and minimising inventory levels. It promotes better visibility and information sharing, enabling partners to make more informed decisions and respond quickly to market demands. Additionally, collaboration allows for more sustainable operations by reducing the environmental and social externalities of freight transport (Aloui et al. 2021; Grote et al. 2023; Serrano et al. 2017). Moreover, the emergence of new technologies and innovative business models has created numerous opportunities and significantly fostered collaboration within the logistics sector, paving the way for a greater prevalence of collaborative systems (Y. Wang and Sarkis 2021). However, collaboration also presents its fair share of challenges. One of the primary challenges is establishing trust and building strong relationships among partners, as collaboration requires sharing sensitive information and aligning interests. Coordinating diverse stakeholders with different priorities, organisational cultures, and systems can be complex and time-consuming. Additionally, collaboration often requires investment in technology infrastructure, data-sharing platforms, and establishing effective communication channels. Overcoming these challenges necessitates clear governance structures, effective communication, and a commitment to building mutual trust and shared goals among collaborators (Basso et al. 2019; Daudi, Hauge, and Thoben 2016; Karam, Reinau, and Østergaard 2021; Vargas, Patel, and Patel 2018).

LSPs play a pivotal role in facilitating and driving collaboration initiatives. Acting as intermediaries, LSPs bring together companies with similar logistics needs, leveraging their expertise, infrastructure, and network capabilities to enable collaboration. Therefore, they can bring together actors from different levels of the supply chain, for example by pooling shipments, consolidating transport resources, and sharing warehouse space (X. Wang, Persson, and Huemer 2016). LSPs can also practice horizontal collaboration with other LSPs by coordinating route scheduling and planning, optimising backhaul operations, engaging in freight exchanges, and jointly optimising vehicle fleets (Vargas, Patel, and Patel 2018). However, the increased emphasis on collaboration also brings forth challenges commonly associated with such initiatives, including the need for accepted mechanisms to allocate revenue among collaborating parties (Audy et al. 2012; Guajardo and Rönnqvist 2016), as well as the delicate task of sharing information with direct competitors (Raweewan and Ferrell 2018).

2.2. Simulation models applied to logistics

To address these challenges, it is essential to understand the impact of horizontal collaboration on individual players and the wider logistics system. The field of OR provides valuable tools to optimise multiple decision problems arising from collaboration and to evaluate the consequences of new collaboration schemes, supporting the development of efficient systems that are sustainable over time.

Table 1. Studies on simulation models applied to logistics.

Paper	Context	Collaboration	Multimodal	Disruptions	Dynamic requests
(Sarraj et al. 2014)	Long-haul	X	x		X
(Sprenger and Mönch 2014)	Long-haul	X			x
(Reis 2014)	Long-haul		x		x
(Furtado and Frayret 2015)	Long-haul	X	x		x
(Kurapati et al. 2018)	Long-haul		x	x	
(de Bok and Tavasszy 2018)	Urban		x		
(Fikar, Hirsch, and Nolz 2018)	Long-haul		x	x	
(Ambra, Caris, and Macharis 2019)	Long-haul		x	x	
(Elbert, Knigge, and Friedrich 2020)	Long-haul	x			x
(van Heeswijk et al. 2020)	Urban	x			x
(Gómez-Marín et al. 2020)	Urban	x		x	x
(Sakai et al. 2020)	Urban		x		
(Bae et al. 2022)	Urban	x			x
(Kaddoura et al. 2024)	Long-haul		x		

Numerous studies have been conducted to evaluate the impact of horizontal collaboration in logistics networks and to assess the benefits and challenges associated with collaboration (Aloui et al. 2021; Pan et al. 2019). Agent-based simulation, in particular, is a valuable tool due to its capabilities to model the behaviour of different agents and capture their interactions in great detail, providing the opportunity to study emergent behaviours that are not evident in initial design stages (Okdinawati, Simatupang, and Sunitiyoso 2015).

Simulation-based approaches offer several advantages in evaluating the impact of collaboration. They provide a controlled and replicable environment to test different collaborative strategies and scenarios, which may be challenging or costly to implement in real-world logistics networks. Multiple agent-based models have been proposed to analyze logistics networks, leveraging the flexibility offered by these techniques (Clausen et al. 2019; Gómez-Cruz, Loaiza Saa, and Ortega Hurtado 2017). In the logistics domain, simulation models are typically employed to address operational problems, allowing researchers to test the performance of various operational schemes under different scenarios. Table 1 provides an overview of studies that have proposed simulation models applied to logistics, indicating the context of the problems being addressed (urban or long-haul). It is also identified if these studies consider or not relevant aspects for this research, in particular: collaboration schemes, use of multimodal transport, occurrence of disruptions that affect the operations, and the arrival of dynamic transport requests to the system.

The models in Table 1 cater to specific situations, including the examination of logistics in urban environments (de Bok and Tavasszy 2018; Gómez-Marín et al. 2020; Sakai et al. 2020; van Heeswijk et al. 2020), disaster relief operations (Fikar, Hirsch, and Nolz 2018), and multimodal operations (Kaddoura et al. 2024; Reis 2014). Furthermore, studies have proposed models to analyze the impact of collaboration schemes in freight transport, such as scenarios involving multiple operators sharing fleets (Furtado and Frayret 2015; Sprenger and Mönch 2014), the planning of truck platooning (Elbert, Knigge, and Friedrich 2020), the functioning of physical internet operations (Bae et al. 2022; Sarraj et al. 2014), as well as synchromodality (Ambra, Caris, and Macharis 2019; Kurapati et al. 2018). These diverse studies underscore the versatility and applicability of agent-based simulation models in addressing various aspects of logistics operations. However, they also highlight a significant gap: the scarcity of studies that comprehensively model collaboration between LSPs within dynamic environments. The model presented in this paper distinguishes itself from prior works by integrating key concepts from synchromodality, which have not been comprehensively modelled in conjunction before. Specifically, it addresses all the categories delineated in Table 1, unlike the previous models proposed in the literature. Additionally, this model focuses on analyzing the impact on individual LSPs within the collaborative network. Typically, previous research has concentrated on assessing the overall benefit at network level. By studying the individual impacts, the model provides insights into which LSPs may benefit or face challenges in the proposed collaborative scenarios.

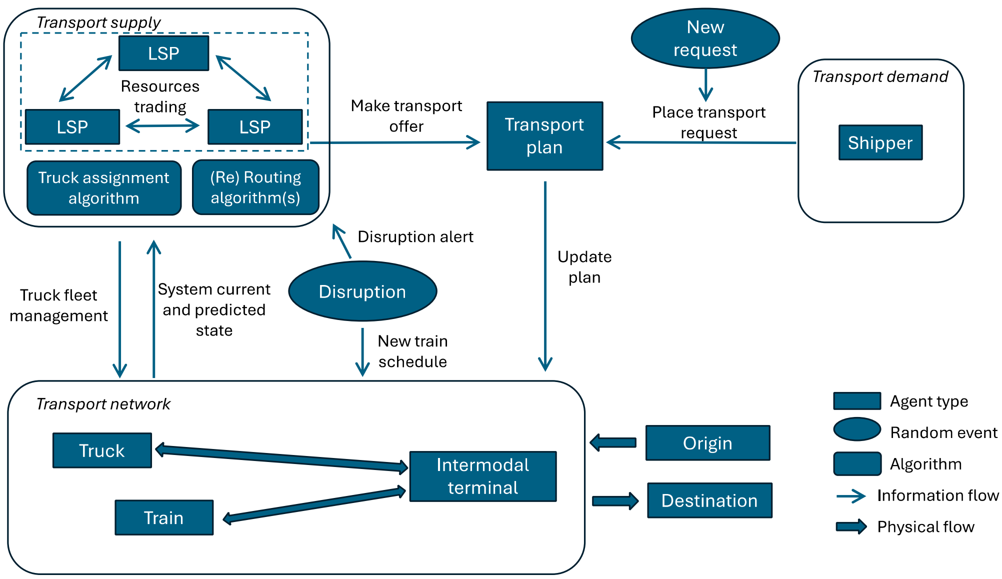

Figure 1. Structure of the simulation model.

3. Simulation model

An agent-based simulation model is developed to depict the operations of a multimodal logistics network within the context of synchromodal transport. This section describes the simulation model and its main assumptions.

3.1. Model structure

Figure 1 provides a broad overview of the proposed simulation model, displaying the primary agent types and their interactions. Further details regarding their attributes, behaviours, and other aspects of the simulated environment are provided in subsequent subsections. Fundamentally, the model encompasses both transport demand and supply sides, along with a transport network comprising infrastructure and vehicles utilised to fulfil the demand. This network operates trains and road transport, linking intermodal terminals with the origin and destination nodes of the transport requests. On the demand side, shippers, in a simplified manner, randomly generate transport requests within the studied area. Conversely, on the supply side, one or more LSPs are responsible for devising transport plans to meet the demand, utilising the resources available on the transport network.

The model addresses the communication and information flow between the different agents. In summary, shippers generate transport requests, which LSPs respond to by providing transport offers, of which the shipper selects the most convenient one. To generate these offers, the LSP considers its own resources (capacity on trains or trucks), as well as information about the current and predicted state of the transport network. In cases involving multiple LSPs, they can trade resources to improve their offers. Moreover, they make use of a routing algorithm to determine the optimal mode and path for each request. Once there is an agreement between the shipper and an LSP, a transport plan is formulated for the request in discussion, which is followed to get the freight to its destination. However, these plans may be affected by disruptions in the network, in which case a new plan might be required to adapt to the new situation. More explanation about the most relevant features of the model is provided in the following subsections.

3.2. Transport demand

The logistics network operates by satisfying transport requests, which are assumed to correspond to homogeneous containers for simplicity. The transport requests are assumed to arrive dynamically to the system during the operations, following a Poisson distribution. Each request is defined by its origin, destination, and a time window. In this paper's experiments, the origin and destination can correspond to intermodal terminals or locations accessible only by truck. The time window specifies the early pick-up time and the late delivery time. The early pick-up time is considered a hard constraint, while the delivery time is treated as a soft constraint, resulting in a penalty if the request is delivered late. The simulation model allows for different time window lengths for each request, as well as variations in the time between request generation and the start of the time window. Therefore, when an order is generated, it might be immediately available for pick-up, or it could be available only after a given period of time. Although the current experiments assume single-container requests for simplicity, the model can easily be adapted to accommodate requests of different sizes.

3.3. Modes of transport

The simulation model aims to represent logistics operations at a regional level, focusing on road and railway transport, which operate differently. Typically, road transport is regarded as more flexible and faster than railways but comes with higher costs and environmental impacts. The authors are currently working on incorporating inland waterways as a third mode of transport into the model. In this regard, it would be interesting to expand the model to also include short-sea shipping transport, given its distinctive operational characteristics. This mode of transport has been identified as a potential alternative with growing relevance for the future (Christodoulou and Woxenius 2019; Comi and Polimeni 2020; Douet and Cappuccilli 2011).

For simplicity, the model assumes road transport facilitated by uniform trucks capable of carrying one container at a time. However, in regional contexts, trucks often have the capacity to transport either one FEU (Forty-foot Equivalent Unit) or two TEU (Twenty-foot Equivalent Unit). An interesting extension of the model would involve allowing trucks to carry two containers, potentially accommodating different requests, although this extension would introduce further challenges or complexities to the modelling process. The presented model focuses on other characteristics of synchromodal operations, where flexibility and real-time decisions are crucial. For this reason, the simulation model incorporates a Geographic Information System (GIS) environment. This allows the modelling of trucks moving within the actual street network, enabling potential mid-route re-routing as discussed in subsequent subsections. The model considers two types of truck operations: trucks owned by LSPs and trucks operated by external providers. Trucks owned by an LSP remain as entities throughout the entire simulation and are based at depots. Thus, the model simulates not only their movement when loaded but also when empty, whether idle or on their way to pick up or return a container. These trucks can be assigned to serve multiple requests sequentially, with constraints ensuring their return to the depot after a specified threshold. On the other hand, trucks operated by external providers are assumed to be always available to LSPs for outsourcing road transport. In the simulation, these truck entities are generated when and where required and are removed once they deliver their cargo. They incur higher transport costs to account for unmodeled empty trips and the profit margin set by external providers.

Unlike trucks, trains adhere to predetermined schedules indicating the sequence of terminals visited by each train service, along with respective arrival and departure times. Train services have specific capacities, which can vary across different legs of the service. This is because although trains are assumed to have constant capacities, in practice, most of that capacity is booked months in advance, often by actors outside the modelled system. For these experiments, the interest lies in the remaining capacity in the short term, assumed to be booked and assigned in the spot market during the simulation horizon.

3.4. Logistics service providers

The model can accommodate one or more LSPs, serving as the agents responsible for routing requests and executing transport plans. When multiple LSPs are present, the model assumes the existence of a communication platform connecting them, as well as with the customers. Consequently, when a transport request is placed, all LSPs submit offers with specified prices, allowing the external customer to select the cheapest offer. These offers are generated using a routing algorithm (described in the next section) that considers the resources available to the respective LSPs, including truck and train capacity. Each LSP may possess a fleet of trucks based at one or more depots, which they can utilise to transport containers, incurring transport costs based on the distance. As mentioned before, LSPs can also outsource truck trips at a higher unit cost. Regarding train capacity, LSPs can have reserved train slots for specific train services, which were booked in advance and can be used without incurring extra costs. Additionally, they can book additional train capacity in the spot market if available.

The aim of the LSPs in this model is to maximise their own profits, which is calculated as the difference between the revenues and the operating costs. The revenues are obtained according to the price of the requests that were granted to him, and eventually from the services traded with other LSPs. On the other hand, the costs are related to the distance travelled by their trucks, the cost of outsourced truck services, additional train capacity, as well as transshipment, holding, and late delivery costs for the awarded requests.

3.5. Assigning and routing transport requests

To make an offer for a transport request, LSPs must determine the best route and mode combination, taking into account the available resources (capacity) and the current and planned status of the system, such as the current position of their trucks and the planned itinerary for each of them. The current version of the model performs routing for individual requests, assuming that they arrive dynamically, one at a time. However, the simulation can be modified to incorporate algorithms for optimising the routing of multiple requests simultaneously if necessary.

The pseudocode of the current routing algorithm is given in Algorithm 1. This algorithm searches for all feasible multimodal paths under a few constraints. The main constraints considered are that: intermodal terminals can only be visited once by a container, trucks can only be used for transport from the origin and/or to the destination, and the request must satisfy its time window. When generating the alternative routes, firstly the algorithm considers the direct truck connection, which is considered to be always feasible. Then, to find the feasible multimodal paths, the algorithm systematically checks all feasible combinations of intermodal terminals connected by train services, potentially allowing several train legs. In these multimodal paths, trucks are used for the initial and final drayage operations, if necessary. The algorithm works backwards, branching and extending the potential paths by sequentially adding intermodal terminals to the route, as long as the path remains feasible. To determine if a terminal insertion is feasible, the algorithm checks every train service connecting the pair of terminals, verifying in each case if there is sufficient train service capacity and if the train's departure and arrival times are consistent with the required time window. Also, the truck travel time from the Origin and to the Destination nodes is considered in the feasibility check. The process is repeated iteratively, until all feasible paths are generated. Then, the cost of each path is calculated to select the most advantageous one.

The cost of the potential paths is calculated including transport costs for each mode of transport (proportional to the distance travelled), a fixed transshipment cost, a cost for holding the container at terminals, and eventually a late delivery penalisation (proportional to the delay time). It is worth noting that paths with late delivery are only considered if no other options meet the time window requirements. Moreover, in the experiments shown in this paper, there is no penalisation for early delivery, but that could be easily implemented into the model. When calculating the costs, the algorithm also checks the availability of trucks for each truck leg, to determine the corresponding transport cost. The

Algorithm 1: Pseudocode for the routing algorithm

```
Define set of incompletePaths
Define set of completePaths
//Generate path by truck only
Create the initial path (path0) by truck from the Origin to Destination
completePaths.add (path0)
//Generate multimodal paths
for each terminal T1
   path1 ← new empty path
   path1.add(T1) //add a leg from T1 to Destination by Truck
   Check the feasibility of path1 (based on the time constraints and truck travel times)
   if feasible: incompletePaths.add (path1)
end for
//Extend the multimodal paths backward:
while size of incompletePaths > 0
      get path1 from incompletePaths
   T1 ← first terminal visited in path1
   for each terminal T2
      for each train service between T2 and T1
         path2 ← a copy of path1
         path2.add(T2) //add leg from T2 to T1 considering the specific train service
         Check the feasibility of path2
         if feasible: incompletePaths.add (path2)
      end for
   end for
   completePaths.add (path1) //Considering truck connection from Origin to T1
   incompletePaths.remove(path1)
end while
//Select the cheapest path
for each path in completePaths
   calculate the totalCost
end for
Return the path with minimum totalCost
```

algorithm checks whether the leg can be served by the fleet or if the service needs to be outsourced. In the case of using a fleet truck, the algorithm determines the best way to incorporate the current request into the truck's planned route (if it exists), by testing the insertion of the new request between the different requests already assigned to that truck and selecting the optimal one. This way, the additional distance travelled by the truck is included in the pricing for this request. Finally, the offer price is assigned for the selected path. In the current model, the price is simply determined by adding a fixed margin to the expected cost. However, more complex models could be incorporated into the simulation, such as dynamic models considering remaining capacity and forecasted demand.

Once all LSPs have submitted their offers, the cheapest one is selected, and the request is assigned to the respective LSP. Currently, the model only considers economic costs for assignment. However, the model could potentially incorporate additional elements such as environmental and social costs, as well as factors like LSP reliability or past relationships between customers and LSPs.

3.6. Disruptions and re-routing

To assess the impact of reaction strategies in a synchromodal system, the simulation model introduces disruptions in the form of train service delays and cancellations. Cancellations can involve either an entire service or a segment of it, starting from an intermediate stop and continuing until the final stop. In the case of service delays, a revised schedule is issued for the affected train service, maintaining the sequence of terminals visited while updating arrival and departure times. It's important to highlight that the proposed model does not optimise this aspect; rather, the new schedules are treated as external inputs, with the updated times being generated randomly. Disruptions are stochastically generated during the simulation and can affect running train services or those scheduled for the future.

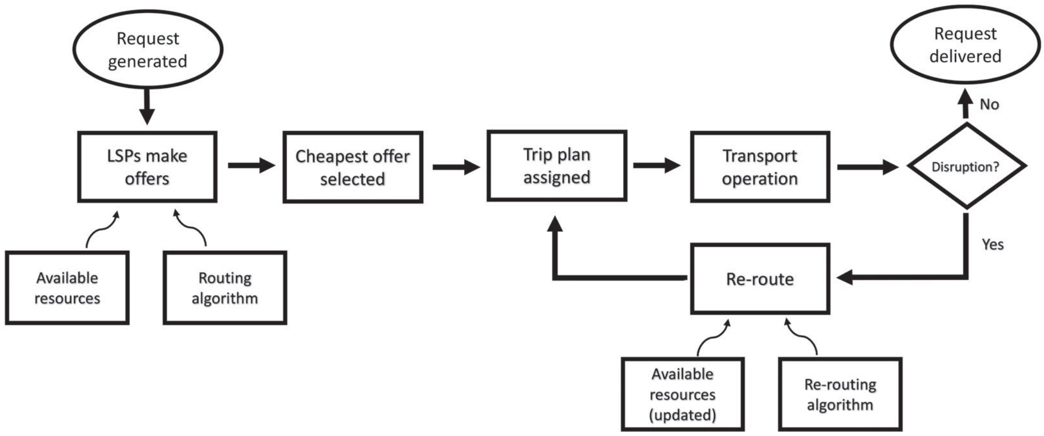

Figure 2. Schematic view of a request's flow in the simulation model.

Although short notice significant disruptions are uncommon in normal operations, they can occur and part of the focus in this research is to determine how more flexible operations can react to such events. Therefore, these kinds of events, such as last-minute train cancellations, are allowed in the experiments presented in this paper.

Once a disruption occurs, the model examines all affected transport requests, and a re-routing algorithm is executed for each of them. The re-routing algorithm is similar to the routing algorithm described earlier, with a few differences. In the case of re-routing, the assigned LSP remains the same, so there are no offers from other LSPs. If the transport plan for the request is already in progress, the current status of the request is considered during re-routing. For example, if the respective container is currently being transported by truck, the truck may either continue its route or be re-routed to a new intermodal terminal to catch a different train service. Conversely, if the container is currently on a train, it must reach at least the next stop of that train service before deciding whether to continue with the original plan or establish a new one. To summarise, Figure 2 presents a schematic view of the different steps followed by a transport request in the modelled system.

4. Numerical experiments

In this section, we present the experiments conducted to test the proposed simulation model and to evaluate the impact of horizontal collaboration between LSPs in a logistics network. The objective is to compare different scenarios and analyze the outcomes of collaborative and competitive approaches. Additionally, the experiments focused on examining the effects of collaboration on the overall system and individual LSPs. The results provide insights into the benefits and challenges associated with collaboration in the logistics industry.

4.1. Tested scenarios

The main objective of this paper is to test the impact of horizontal collaboration between LSPs in the logistics network. To this end, different scenarios were defined to compare different situations, which are outlined in Table 2.

Firstly, two scenarios were defined regarding the degree of collaboration between LSPs: competitive and collaborative. In the competitive scenarios, which represent a business-as-usual situation, LSPs perform their operations and make their offers using only their own resources and the option to outsource to external providers, as described in the previous section. Conversely, in the collaborative scenario, it is assumed that LSPs can trade truck services and train capacity. In this case, when making

Table 2. Tested scenarios.

Experiment id	Size scenario	Collaboration scenario
0	Balanced	Competitive
1	Balanced	Collaborative
2	Imbalanced	Competitive
3	Imbalanced	Collaborative

Table 3. Parameters used in the numerical experiments.

Parameters	Unit	Value
Requests' arrival rate	requests/day	400
Truck transport cost (fleet)	€/container∗km	1
Truck transport cost (external)	€/container∗km	2.5
Rail transport cost	€/container∗km	0.65
Transfer cost	€/container	25
Holding cost	€/container∗h	0.01
Late delivery costs	€/container∗h	10
Truck speed	km/h	60
Max tour time for fleet trucks	h/day	10

their offers, if an LSP does not have an available truck or enough train capacity for a given segment, it can request them from another LSP that has some unused capacity, paying an additional percentage for the service. However, this additional cost is generally lower than the cost of outsourcing.

Secondly, two scenarios are defined regarding the relative size of the different LSPs: balanced and imbalanced. In the balanced scenario, all LSPs have a similar number of trucks, and an equivalent number of train slots reserved in advance. On the other hand, in the imbalanced scenario, it is assumed that one of the LSPs is considerably larger in size, concentrating around 60% of the combined truck fleets and reserved train capacities. In the experiments presented in the next section, the LSP that concentrates the resources is denoted as LSP0. These scenarios are used to test how the gains of horizontal collaboration are distributed between the different LSPs and how the size of the players impacts that distribution.

4.2. Characteristics of the tested instance

The experiments are performed using a synthetic instance that was generated inspired by real data from the Benelux region (Belgium, The Netherlands, and Luxembourg). The instance consists of a network with 27 intermodal terminals, 35 origin/destination locations only accessible by truck, and 21 truck depots. The geographical distribution of these locations is displayed in Figure 3. For the experiments presented in this paper, three LSPs are considered. The combined fleet between the three LSPs consists of a total of 42 trucks. The experiments correspond to a simulation horizon of 1 week, in which there are 95 train services, which were generated arbitrarily. The transport requests are generated stochastically, using a predefined arrival rate, and the origin and destination being selected randomly. For each request, the release time and the length of the time window are also randomly generated using a uniform distribution. Other relevant instance parameters are displayed in Table 3.

4.3. Experimental results

Since the simulation model corresponds to a stochastic model, 10 replications were run for each experiment, and here the average results for each experiment are presented. In general, for the relevant outcomes discussed below, the experiments yielded an error rate below 3% with a 95% confidence level. All the experiments are conducted on Mac OS, on Intel® Core™ i7 2.6 GHz machine with 16.00 GB RAM.

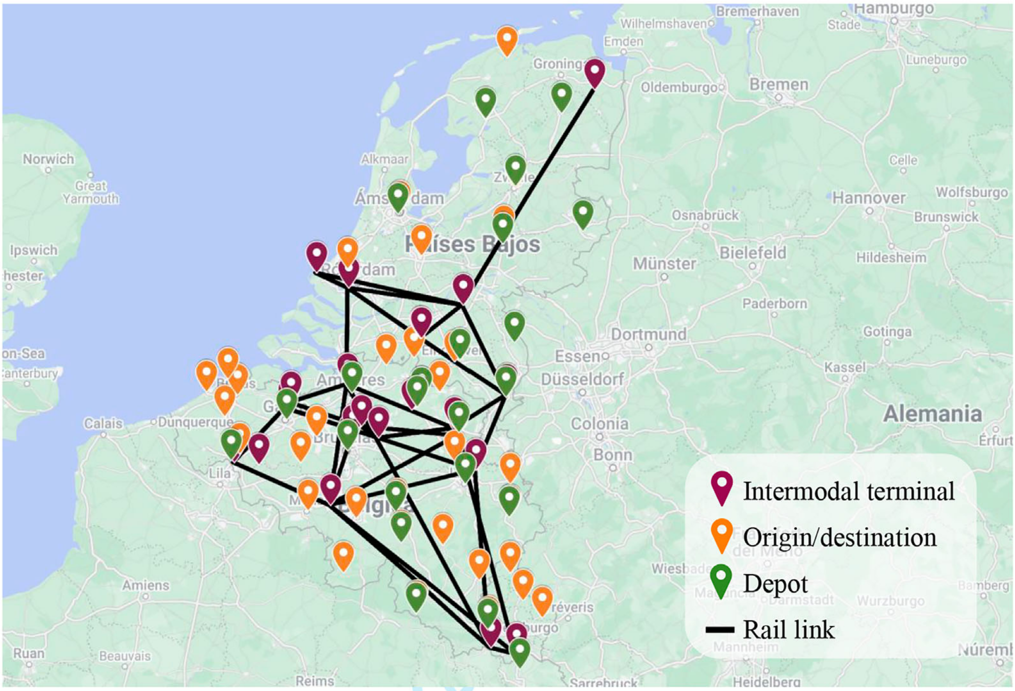

Figure 3. Visualisation of locations in test instance.

In the first set of experiments, the simulation is executed to test the impact of collaboration for the system as a whole. By comparing the results of the competitive and collaborative scenarios, it is observed that the total profits for the system increase by approximately 6%. Moreover, the collaborative scenario leads to an increase in the share of requests using the train at least in one section of their trips, from 39% to 42%. This increase is also reflected in an increase in the utilisation of the available train capacity. Overall, these results show that collaboration allows for a more efficient use of the available resources. Furthermore, the collaborative scenario presents a higher average lead time for the requests, which increases by approximately 3.5%. However, this is not reflected in an increase in late deliveries. In fact, the results for collaboration lead to a slight decrease in the percentage of requests with late delivery, although in both scenarios, this percentage is very low, below 0.5%. This shows that the increase in the average lead time does not compromise the service quality, as the initial quality constraints are still satisfied.

The results described above show the impact of collaboration on the overall logistics system. However, the focus of this paper is to explore the impact on individual LSPs and identify how these gains are distributed. Table 4 shows the results for individual LSPs in each experiment. Four experiments are defined, obtained by the combination of the LSP size scenarios and the collaboration scenarios. For each LSP (denoted LSP0 to LSP3) and in each experiment, Table 4 shows the average number of requests that are transported on individual legs (meaning that requests with multimodal paths are counted more than once) and the average profits during the simulation horizon. For a better illustration of these results and the comparison between scenarios, Figure 4 and Figure 5 display the results for the balanced and imbalanced scenarios, respectively.

As seen in Figure 4, in the balanced scenario, there is an increase of approximately 5% in the total number of transport legs executed by the LSPs, due to the increase in requests transported with multimodal paths. It can also be seen that this increase is evenly distributed among the three LSPs, and this is reflected in an even improvement in the LSPs' profits. However, there are some differences in

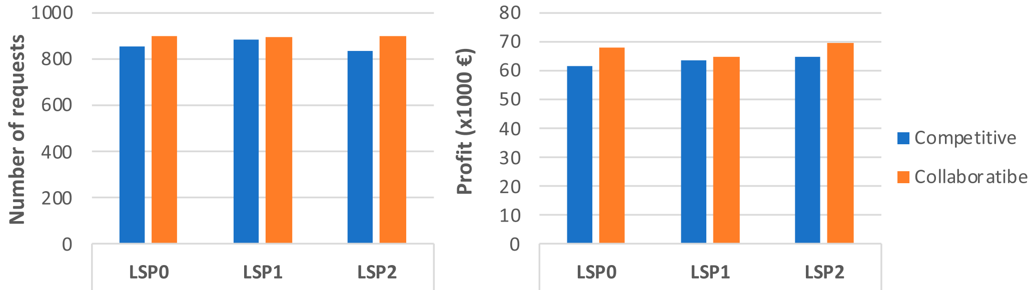

Figure 4. Comparison of results for the balanced scenario (Experiments 0 and 1).

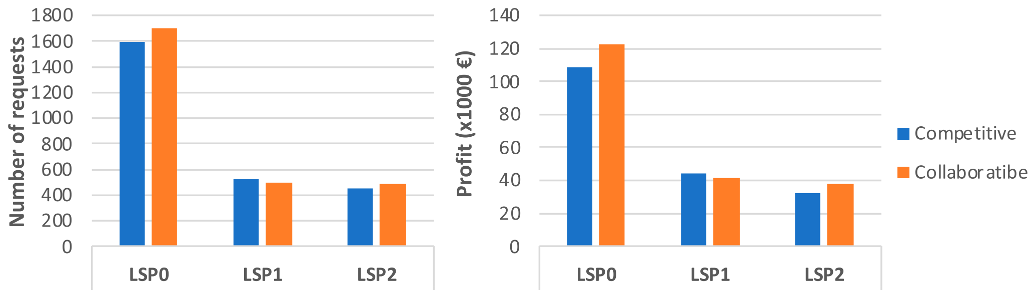

Figure 5. Comparison of results for the imbalanced scenario (Experiments 2 and 3).

Table 4. Results on the tested scenarios.

Experiment id	LSP	Number of requests	Profit (€)
0	LSP0	856	61472
0	LSP1	885	63739
0	LSP2	837	64749
1	LSP0	899	67874
1	LSP1	895	64647
1	LSP2	898	69512
2	LSP0	1595	108759
2	LSP1	523	44253
2	LSP2	452	32339
3	LSP0	1700	122485
3	LSP1	500	41361
3	LSP2	484	38038

the size of the gains, with LSP2 experiencing a relatively smaller increase in profits compared to the other two LSPs. This difference can be explained by the fact that, even if the three LSPs have fleets of the same size, they are based in depots with different locations, which may give an advantage to one LSP over another. Similarly, although all LSPs have a similar amount of rail capacity booked in advance, the specific services in which that capacity is booked vary. Despite these differences, Figure 4 shows that all LSPs benefit from collaboration in this scenario. Thus, participating in a collaboration scheme would be attractive to the potential players, although a distribution scheme would still be needed.

However, the situation is different when the LSPs have different sizes. Figure 5 shows the results for the imbalanced scenario. As expected, in all cases, the larger LSP (LSP0) concentrates a larger amount of transport operations, since it has more available capacity and can make better offers. This larger participation is reflected in considerably larger profits compared to the other LSPs. However, the results show that the gains of collaboration are not evenly distributed. With collaboration, this gap in profits becomes proportionally larger. Indeed, in the imbalanced scenario, although there are more transport operations in total, not all players benefit from it, and LSP1 even experiences a reduction in the number of requests that are transported, resulting in a loss of profits compared to the competitive scenario. On the other hand, LSP0 has a proportionally larger increase in profits, further increasing its dominance in the market. These findings highlight the potential challenges associated with collaboration in an imbalanced LSP ecosystem. While collaboration may lead to increased overall transport operations, the advantages are skewed towards the already dominant players. The imbalanced distribution of benefits raises concerns about the sustainability and fairness of collaborative efforts, as it may hinder the growth and profitability of smaller LSPs. Addressing these disparities and finding ways to promote equitable benefits among LSPs becomes crucial for fostering a healthier and more inclusive logistics ecosystem.

5. Conclusions

In this paper, we developed an agent-based simulation model for a multimodal logistics network. The model incorporates various aspects of the logistics operations in the context of synchromodality, including: dynamic demand generation; multiple modes of transport (road and railway); interaction between different LSPs for assignment and routing of transport requests; and the occurrence of disruptions with the subsequent need for re-routing strategies. The main objective of the paper is to use this model to test the impact of horizontal collaboration between LSPs in the logistics network. To this end, different scenarios were tested, focusing on two main aspects: the degree of collaboration between LSPs, and the relative size of the LSPs. In terms of collaboration, two scenarios were defined: competitive (business-as-usual) and collaborative. Similarly, in terms of relative size, two additional scenarios were defined: balanced and imbalanced.

The results of the simulation experiments yielded valuable insights. Firstly, the collaborative scenarios demonstrated a notable 6% increase in total system profits compared to the competitive (business-as-usual) scenarios. Collaboration facilitated a more efficient utilisation of resources, leading to a higher share of requests utilising train services and an overall increase in the utilisation of train capacity. Although the collaborative scenarios showed a slight increase in average lead time, the percentage of late deliveries remained remarkably low in both collaborative and competitive scenarios. Furthermore, the analysis delved into the impact of collaboration on individual LSPs, revealing a nuanced distribution of gains. In the balanced scenario, collaboration was found to benefit all LSPs, irrespective of their size. However, in the imbalanced scenario, the dominant LSP experienced a substantial surge in the number of requests transported and profits, while one of the smaller LSPs suffered a reduction in participation and profitability.

Overall, the simulation experiments underscored the significant advantages of horizontal collaboration in a logistics network. It enhanced overall profitability, improved resource utilisation, and had the potential to yield fairer outcomes for LSPs. Nonetheless, it became apparent that a fair distribution mechanism for the revenues is crucial to ensure attractiveness and long-term sustainability. Strategies from game theory and other relevant fields could provide valuable insights for future research, helping to address the distribution challenges within collaborative logistics systems. Alternative mechanisms could be incorporated into the proposed simulation model to study emergent behaviours and the impact of such strategies in the complex scenarios represented by this model.

Future research endeavours can extend the simulation model by incorporating additional factors, such as gain distribution schemes, complex negotiation logics between LSPs and customers, as well as environmental and social costs. It is important to note that the findings presented here are based on a synthetic instance generated using data from a specific geographical region, and further validation using larger real-world instances is necessary to generalise the conclusions to diverse contexts. In summary, this study advances our understanding of the impact of horizontal collaboration in logistics networks and highlights the need for fair distribution mechanisms. The simulation model developed serves as a foundation for future research in this field, fostering sustainable and inclusive logistics ecosystems.

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