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# Agent-based solving of the 2-echelon Vehicle Routing Problem

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## Abstract

Building (urban) logistic networks is complex. It also includes the question of network design: Using a direct (one-tier) transport system from the depot to the customer. Or is it better to implement a two-echelon distribution system, transporting the goods with large vehicles to a transshipment hub near to the customer and smaller vehicles for the last-mile distribution. These decisions must be made by the Logistic Service Provider (LSP).

In this study, we investigate the behavior of an LSP in an agent-based simulation framework with different plans: direct delivery, and delivery via a hub. Depending on different input values, e.g. fixed and variable costs of the vehicle, or costs for the hub, the LSP performs its planning and selects the plan with the best score. Tour planning at different stages of the LSP's transport chains is done by solving a Vehicle Routing Problem (VRP). As a result, we have shown, that the LSP selects the best plan in an artificial grid scenario and in different simulation settings, with different number of jobs, cost settings, and a vehicle-type specific cordon toll. In the next steps, we will apply it to existing case studies in large cities, such as Berlin, Germany.

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*Keywords:* 2-echelon; Vehicle Routing Problem; agent-based; transport simulation; freight; logistics

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## 1. Introduction and Motivation

Reducing Greenhouse Gas (GHG) emissions is one of the current major objectives to go towards a (more) sustainable future. For this, the countries participating in the 21<sup>st</sup> session of the *Conference of the Parties to the United Nations Framework Convention on Climate Change* agreed to limit global warming to below 2°C above pre-industrial level ([United Nations, 2015a](#)). Making cities and human settlements resilient and sustainable is one of the 17 Sustainable Development Goals of the United Nations. This includes in target 11.2 a "sustainable transport system for all, improving road safety" ([United Nations, 2015b](#)) and in target 11.7 the "universal access to safe, [...], green and public spaces" ([United Nations, 2015b](#)).

In 2019, the European Commission agreed on the "European Green Deal". Aims include the decoupling of the economic growth from resource use and achieving zero net GHG-emissions by 2050 ([European Commission, 2019](#)). To achieve this, one of the European Commission's targets is the reduction of emissions from transport by 90% by 2050. Various countries have also defined their own climate protection plans, such as Germany's "Climate Action

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Plan 2050" (BMUB, 2016), which aims to reduce GHG-emissions from the transport sector by 40% by 2030 compared to 1990. Within the German transport sector, the road freight transport is responsible for 35% of the  $CO_2$  emissions (BMUB, 2018).

Electrification of the transport sector could be an appropriate solution to achieve these goals, e.g. by replacing today's Internal Combustion Engine Vehicles (ICEVs) with Battery Electric Vehicles (BEVs).

This issue is increasingly discussed due to the changes in urban areas (Caggiani et al., 2020; Oliveira et al., 2020). One idea is to avoid driving with ICEVs in urban areas. Instead, they could be replaced with either BEVs or cargo bikes. Because of their limited range/capacity, it is no longer possible to deliver goods directly from the depot to the customer (Ewert et al., 2021; Hiermann et al., 2019). This leads to the need for local (transshipment) hubs for a more local delivery with smaller vehicles. These hubs need to be connected to the existing main depot(s). Especially for parcels, the last mile delivery with cargo bikes is expanding. Advantages of e-cargo bikes are explored, for example, by Gruber et al. (2014).

This raises the issue of building up or updating (urban) logistics networks, which is complex. Besides all the restrictions coming from the demand side, e.g. locations, quantities, or time-windows of the jobs, there is also the question of the network design: Should there be only one tier (direct delivery)? Or is it better to have a two-echelon distribution system, using large vehicles to transport goods to transshipment hubs close to the customers, and use smaller, environmentally vehicles for the last-mile distribution (Oliveira et al., 2022)?

Since the range of BEVs is no longer the main issue, there is a new trend: Banning or charging (large) vehicles not meeting certain requirements from the inner-city. This can be done either for *environmental reasons*, by introducing a Low Emission Zone (LEZ), see e.g. in Greater London, where Heavy Goods Vehicles (HGV) with old emission standards must pay £300 (approx. 350 €) a day for entering the London LEZ (Transport for London (TfL), 2022b). In most of London there is also an additional Ultra Low Emission Zone (ULEZ) with stricter environmental requirements. A charge of £12.50 (approx. 14.50 €) is imposed on vehicles not meeting these requirements (Transport for London (TfL), 2022c).

LEZs, which prohibit certain types of vehicles from entering certain areas of a city, can be found in other European countries as well: In Germany, for example, Berlin has implemented a LEZ with the explicit midterm goal to modernize the vehicle fleet (Senatsverwaltung für Umwelt, Verkehr und Klimaschutz Berlin (SenUVK), 2017). In France, several cities have also introduced temporal LEZ (Ministère de la transition écologique et de la cohésion des territoires, 2022). Another reason for reducing or banning (larger) vehicles from cities is *road safety*: In Greater London, trucks over 12 tons gross vehicle weight are required by the Direct Vision Standard (DVS) to a certain level of direct view from the driver's cabin for entering or operating in Greater London. It is part of "the vision zero plan to eliminate all deaths and serious injuries on London's transport network by 2041" (Transport for London (TfL), 2022a).

In response, either significantly more small vehicles will be needed to transport goods from depots to customers, or a further two-echelon distribution network will be used. The two-echelon network allows the transport of goods with large vehicles from the (main) depot to the transshipment hub(s) located near to the ban-area. From there, the last-mile delivery is done by small vehicles that are allowed to enter the zone.

The Logistic Service Provider (LSP)<sup>1</sup> is the organizer of the transport chain and the transport of the goods from the sender to the receiver using the network (Schröder et al., 2012). Schröder et al. (2012) decided, in their multi-agent freight transport model, to have separate agents for the LSP and the *carriers*. While the LSP agent organizes the transport chain, the carrier agent is designed to model a transport operator (Schröder et al., 2012). It plans and models the transport on individual parts of the transport chain.

This paper is organized as follows: A brief review of related literature in the area of two-echelon Vehicle Routing Problems is presented in Section 2. Section 3 provides an overview of the methodology and software used for the following simulation experiments. Section 4 presents a first proof-of-concept study using a simple simulation experiment. In Section 5, an extended simulation experiment is conducted with more jobs, an increased demand, and a vehicle type specific toll. The paper closes with a conclusion and outlook (Section 6).

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<sup>1</sup> We decided that we will use the term LSP instead of Transport Service Provider (TSP), as done by (Schröder et al., 2012), because TSP is often used as acronym for Traveling Salesman Problem.

## 2. Related Literature

Oliveira et al. (2022) summarize some of the relevant two-echelon Vehicle Routing Problem (2E-VRP) types and their history in the context of city logistics. According to Oliveira et al. (2022), the first formal definition of a two-echelon (capacitated) Vehicle Routing Problem (2E-CVRP) was given by Perboli et al. (2008). Nevertheless, Crainic et al. (2004, 2009) are said to be the first who address the application of the two-echelon distribution systems in the context of city logistics (Oliveira et al., 2022). Enthoven et al. (2020) explore the application of the 2E-VRP in urban distribution, especially for e-commerce. They show that using a parcel locker to serve customers in the same area can significantly reduce driving distance. They distinguish their Two-Echelon Vehicle Routing Problem with Covering Options (2E-VRP-CO) from a location routing problem as described by Prodhon and Prins (2014), highlighting that direct visits during the delivery process are not necessary for every customer.

Hiermann et al. (2016) take a different approach to address the challenges with BEVs and their limited range, by introducing the Electric Fleet Size and Mix Vehicle Routing Problem with Time Windows and recharging stations (E-FSMFTW). It includes the choice of recharging times (when?) and locations (where?) into the actual vehicle routes. Implementations of 2E-VRP with synchronization between vans and bicycles are done, for example, by Anderluh et al. (2017, 2019). Wang et al. (2019) propose the combination of ICEVs in the first and BEVs in the second tier. Caggiani et al. (2020) solve a Two-Echelon Electric Vehicle Routing Problem with Time Windows and Partial Recharging (2E-EVRPTW-PR) as a green logistics solution for last-mile deliveries, considering synchronization between e-vans and e-cargo-bikes. Instead of using e-vans to deliver goods directly from the depot to the customer, they use the e-vans for a first tier and reload the goods for the last-mile delivery with e-cargo-bikes in traffic restricted areas. Bakach et al. (2021) show that the use of delivery robots on the second tier can save about 70%, up to 90%, of the operating costs compared to conventional truck-based deliveries. A similar study for delivering of parcels or small commodities in pedestrian areas or residential clusters using unmanned vehicles at the second tier is conducted by (Yu et al., 2020). Boysen et al. (2018) mixes up the idea of using small autonomous vehicles, without having hubs for the transshipment between the first and the second tier. Instead, they consider delivery robots that are transported and dropped off by large vehicles. The interconnection of different transport modes in two-echelon-models is studied, for example, by Li et al. (2021): They combine ground and unmanned aerial vehicles. In particular, they shed light on the emerging complexity of operations at hubs when considering the two modes.

The tradeoff between customer satisfaction and emissions savings in the design of the delivery process is investigated, for example, by Wang and Wen (2020). In their Low-Carbon Two-Echelon Heterogeneous-Fleet Vehicle Routing Problem (LC-2EHVRP), they find that the introduction of a soft delivery window can lead to a reduction in carbon emissions while maintaining optimal customer satisfaction. Li et al. (2016) optimize their Two-Echelon Time-Constrained Vehicle Routing Problem (2E-TVRP) in terms of emitted carbon emissions per ton-mile by changing the hub location or minimizing empty trips.

Other studies on the 2E-VRP have also taken into account the management of inventory and the storage of goods: Qiu et al. (2021) apply the two-echelon production routing problem to hubs with cross-docking functionality. Their study highlights the importance of handling costs in determining the optimal solution. Guimarães et al. (2019) establish a connection between the two-tier supply chain and inventory management. In this context, the intermediary, located between the two tiers, is responsible for ensuring an adequate supply of incoming goods from suppliers and outgoing goods to customers. A recent development in logistics is considered by Darvish et al. (2019). They additionally investigate the possibility of flexible warehousing, thus adding the location of the hub to the optimization problem. Their study of a Flexible Two-Echelon Location Routing Problem (2E-FLRP) shows an average saving of 30% when both the flexibility of time frame and the hub location are combined.

## 3. Methodology and Software

### 3.1. Methodology

We are using Multi-Agent Transport Simulation (MATSim) as an agent-based simulation framework for large-scale transport simulations. It is programmed in Java and the source-code and many scenarios are available as open-source/open-access scenarios (Horni et al., 2016).

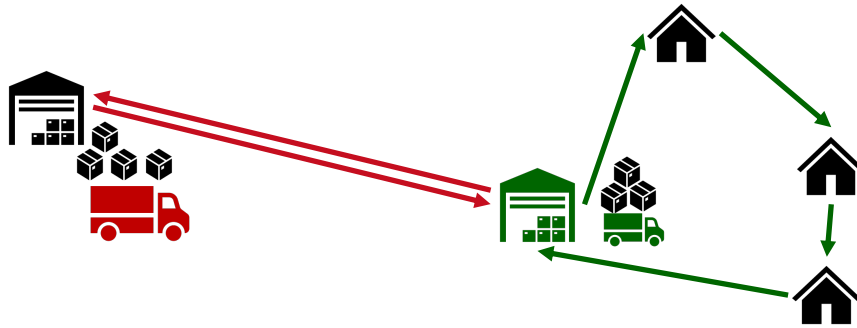


Fig. 1: Example of a two-echelon distribution network: The large vehicle (red) transports the goods from the depot (left) to the hub (center). From there, the last-mile distribution is done by a smaller vehicle (green).

MATSim already has a so-called *freight* component. Here, *carriers* have *vehicles* as *resources*, for which they plan *tours*. Tours either fulfill *shipments*, where goods need to be transported between locations, or *services*, where only the corresponding locations need to be reached.

In the present paper, LSPs are added, which have *hubs* as their resources and can recruit carriers. That is, LSPs organize and consolidate logistics operations. LSPs and carriers can be vertically integrated, but do not have to. The overall ontology and prototypical implementation for LSPs stems from [Matteis et al. \(2019\)](#); the present paper uses that framework to address a practical problem.

The use of LSPs allows the integrated solving of the transportation problem along the entire transportation chain from the origin to the destination. In general, this is the transport from the *sender* to the *receiver*. In order to fulfill the job(s), the LSP can select between one or more different options (*plans*). It could, for example, either make a direct delivery or it uses a more or less complex hub-and-spoke network. Each of the different LSP *plans* has at least one so-called *solution* ([Matteis et al., 2019](#)). A *solution* is a transport chain from the sender to the customer, including all parts, such as the carriers for the transportation or the hub(s) for reloading.

In our studies, we will focus on the distribution of goods to the customers. Therefore, we define the (last) depot as the origin and ignore the upstream logistic chain, that transports the goods to the (last) depot. Such transport chains can consist of, e.g., only of one *carrier*, which solves its own Vehicle Routing Problem (VRP) for the direct delivery from the depot to the customer. Or it can be a logistic chain using a 2-echelon network. In this case, it is something like a carrier, that transports the goods from the depot to the *hub*, reloads them there, and transports them further with (another) distribution carrier. Figure 1 shows a small example of such a 2-echelon network. The large vehicle (red) transports the goods from the depot (left) to the *hub* (green). From there, a smaller vehicle (green) distributes the goods over the last mile. The specific parts of the logistics chain are not planned in detail by the LSP at this stage: Each carrier solves its own VRP and decides on the specific vehicle(s) and tour(s) to transport the goods.

### 3.2. Software

To simulate freight transport, MATSim provides the *freight* contrib. The freight contrib connects MATSim to jsprit ([Zilske and Joubert, 2016](#); [Zilske et al., 2012](#)). Jsprit is an open-source VRP solver ([jsprit, 2018](#)). The coupling between MATSim and jsprit is shown in Figure 2. The carriers, each defining its own VRP, are converted to jsprit. Each carrier is handled by jsprit independently of all the other carriers. Then the carrier, including the planned tours, is returned to MATSim. MATSim then creates its (driver) *agents* based on these tour plans and feeds them into the normal transport simulation.

Jsprit allows the solving of many subtypes of VRPs with, e.g., multi-depots, time restrictions, capacity constraints, infinite fleets, including the Fleet Size and Mix Vehicle Routing Problem (FSMVRP). Jsprit's algorithm bases on an iterative approach using the ruin-and-recreate principle from [Schrimpf et al. \(2000\)](#). More information about different types of VRP can be found in the literature (see, for example, [Toth and Vigo, 2014](#); [Scheuerer, 2004](#); [jsprit, 2018](#)). In the conjunction with MATSim, it is also possible to solve the VRP based on a time-dependent road network (see, for example, [Martins-Turner et al., 2020](#); [Ewert et al., 2021](#)).

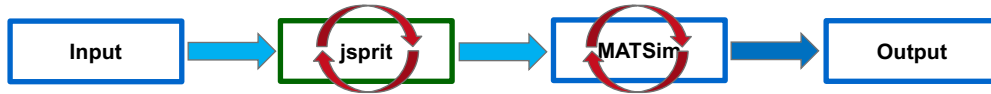


Fig. 2: The MATSim freight contrib (light blue) connects MATSim (dark blue) with jsprit (green). Both MATSim and jsprit usually run over several iterations.

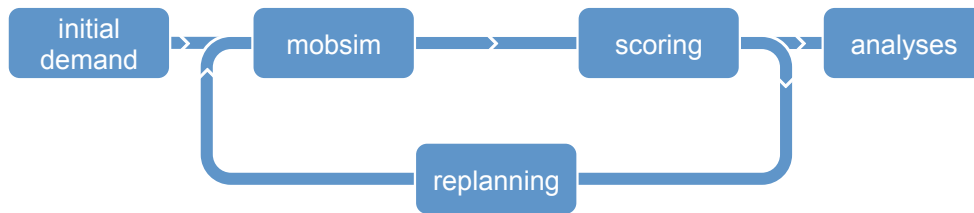


Fig. 3: The MATSim-loop (Source: Horni et al. (2016))

The main limitation is that each *carrier* and its solved VRP only represents one tier of the logistics network. Because of this, it is not possible to address 2-echelon problems, where one or more transshipment hubs may be used on the way from the sender to the receiver. There were earlier studies, e.g. Turner (2015), that have tried to solve this problem by splitting it into two different sub-problems: First, the last VRP from the hubs to the customer is solved as a Multi-Depot Vehicle Routing Problem (MDVRP). From this result, one can derive how many goods are needed at each hub. This is the input to setting up and solving the VRP from the originating depot(s) to the hub(s). This approach lacks the higher authority that is responsible for planning the transport along the entire logistics chain: the LSP.

In the agent-based simulation framework used in the present study, the LSP is the owner of one or more *plans* (Matteis et al., 2019). The LSP's behavior is analogous to MATSim's standard person agents: It selects, executes, and scores one plan per iteration. Figure 3 illustrates this approach. For the first studies, and because there is currently no interaction with other agents, there is only a single strategy for the replanning step: select one of the existing plans. There is *no* strategy implemented to modify/mutate of these existing or create new *LSP-plans*. As a consequence, the possible LSP-plans are defined in advance. For more information on the specific setup of the simulation experiments, we refer to the descriptions in Sections 4.1 and 5.1.

#### 4. Simple Simulation Experiment

As a proof-of-concept study, we run a simple simulation experiment and observe the decision and result of the LSP.

##### 4.1. Simple Simulation Experiment — Setup

**Network.** For this proof-of-concept study, we use a grid network. The network (see Figure 4) consists of  $9 \times 9$  links. Each link has a length of  $\ell = 1\text{km}$  and is one-way. As one can see, each link is a continuous connection, with alternating directions. The free speed on each link is constant with  $v = 30\text{km/h} = 8.333\text{m/s}$ , resulting in a free speed travel time of  $tt_{free} = \ell/v = \frac{1\text{km}}{30\text{km/h}} = 120\text{s}$ . In our study, we will have no congestion.

**Location of the LSP Resources.** As shown in Figure 4, the depot is located in the south (link  $i(5,0)$ ), while the customer awaiting the shipment is located in the center (link  $i(5,5)R$ ). The LSP is implemented with *two plans*, each with *one solution*. The solution of *plan A* is the direct delivery of the shipment from the depot to the customer. The solution of *plan B* is the 2-echelon delivery: From the depot to the hub and from the hub to the customer. The hub is located at link  $j(5,3)$ .

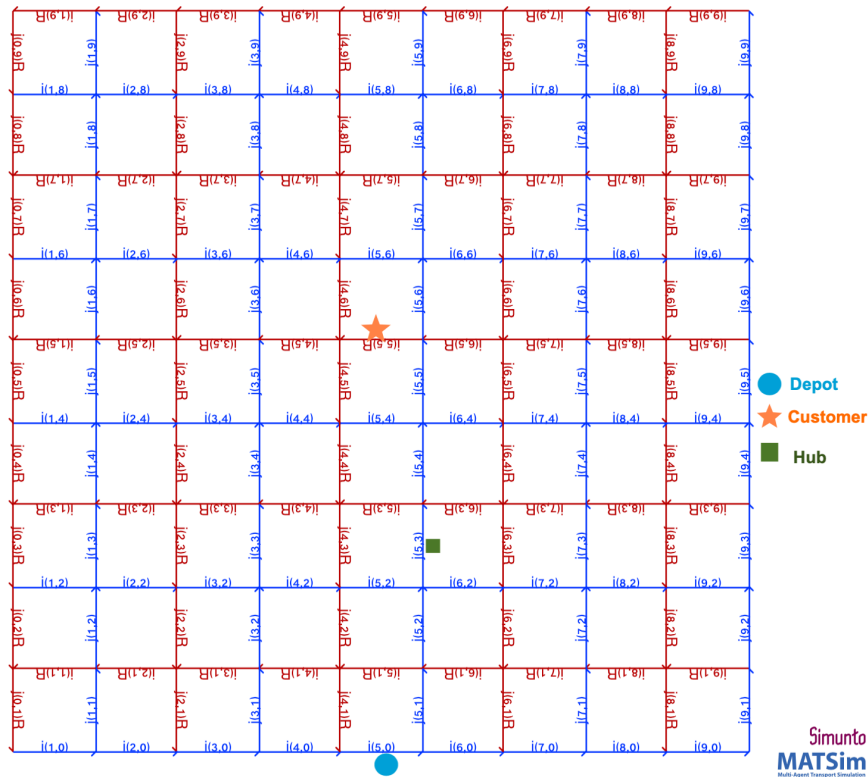


Fig. 4: Simple scenario: The grid network, including the location of the depot (origin), the customer (destination), and the transshipment hub. All roads are one-way. The color indicates the direction: blue: positive direction, red: negative (return) direction.

*Simulation Experiments.* To show that the LSP will make the right choice and select the better plan as expected, we run the scenario several times, each time with a slightly different setup. In all setups, there is only *one* LSP with *two* different plans. Each plan has only *one* solution: Plan A with a direct delivery solution, and plan B with a logistic chain using a hub in between. The simulation is run for two iterations, so the LSP tries and scores its two different plans, and then select the better one.

We have found that in many cases the direct delivery has the lower costs. A relatively lower cost for the two-echelon alternative may occur if, for example, there is a low-cost solution for urban delivery, such as an electric cargo bike, or if the entry of long distance freight vehicles into the urban core by is penalized, e.g. by a toll (Bakach et al., 2021; Yu et al., 2020).

The following cases are considered — see also Table 1:

1. Same transport costs for all carriers. This should lead to the selection of plan A, since the cost is lower (= the score is higher).
2. Highly reduced transport costs for the carrier from the hub to the customer. Because of the significantly lower variable costs for the second stage, plan B has the lower total cost (= higher score) and should therefore be selected.
3. Same as before, but now with additional costs for using the hub. Again, plan A should have the better (higher) score and should therefore be selected by the LSP.

The different cost values are summarized in Table 1a. Table 1b shows the assignment of the carrier types and costs for using the hub to the individual cases. Everything else, e.g. the network, demand, remains the same.



Table 1: Cost parameters for the different simulation setups. Each carrier has only one vehicle type available, so the carrier's costs are equal to the costs of that type. Case 1: Same costs for all carriers, no costs for the hub; Case 2: Costs of carriers starting from the depot are significantly higher than the costs of carriers starting at the hub, no costs for using the hub; Case 3: Same as case 2, but with additional costs for using the depot.

(a) Cost parameters and transport capacity for the different carriers			(b) Carrier type usage in the different simulation setups (cases)				
Solution element	Cost type	Value	LSP-Plan	(solution)	Case 1	Case 2	Case 3
carrier type I	fixed [€/day]	150	A	(direct)	I	I	I
	per distance [€/m]	0.01	B	depot → hub	I	I	I
	per time [€/s]	0.01		hub → customer	I	II	II
	capacity [units]	50		hub [€/day]	0	0	100
carrier type II	fixed [€/day]	25					
	per distance [€/m]	0.001					
	per time [€/s]	0.005					
	capacity [units]	5					
hub	fixed [€/day]	0 or 100					

#### 4.2. Results of the Simple Simulation Experiment

Table 2 shows the results for all cases. As one can see, the score of plan A (direct delivery) remains constant, because it is the same setup in all cases. Plan B (with hub) has a different score for each case. As described in Table 1 (see Section 4), the elements of plan B's solution are modified: For case 2 the costs for the distribution carrier (hub → customer) are reduced. In case 3, this advantage is overcompensated by the costs for the hub. The scores change accordingly, e.g. the score of plan B in case 3 is lower than in case 2 by the 100 EUR hub costs.

Table 2: Resulting scores and the plans selected (by the LSP) for the three different simulated cases. Depending on the setup (costs for the different plan elements of plan B), a different plan is selected. Plan A: direct delivery; Plan B: using a transshipment hub.

Plan	Case 1		Case 2		Case 3	
	A	B	A	B	A	B
score	-285	-480.4	-285	-278.3	-285	-378.3
selected?	x			x	x	

Note that the score has a negative sign. The lower the absolute value of a negative score, the lower the cost and the *better* the plan. The selected plan is marked with (x). One can see that the LSP selects the *better* plan in all cases.

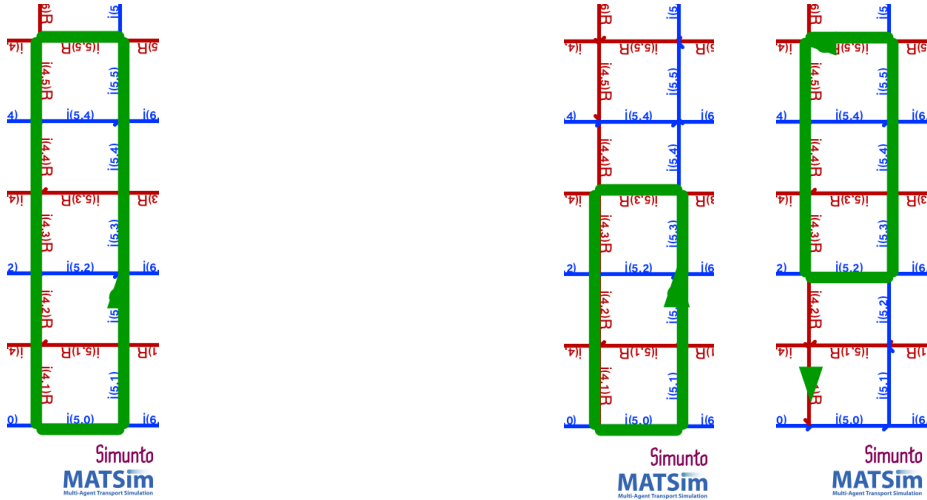
Figure 5 shows the different routes driven by the vehicles in the simulation. Figure 5a is the visualization of plan (A), while Figure 5b shows the two segments of the 2-echelon delivery: depot → hub and hub → customer.

The corresponding shipment schedules are shown in Table 3. For the direct delivery (plan A), there is only the one carrier for the main run. It transports the shipment directly to the customer (see Table 3a). For plan B, one can see that the shipment is loaded by the first carrier (mainCarrier), transported, and unloaded after 361 seconds. It is then handled at the hub and transported by the second carrier (distributionCarrier), where it is unloaded at time 730 (see Table 3b).

The results are rather limited due to the limited scope and demonstrative nature of this study. Nevertheless, we can conclude that the plan selection and thus the behavior of the LSP is in line with the expectations.

## 5. Extended Simulation Experiment

Since we have been able to show that the framework works as expected, the simulation experiment is extended in the direction of the later planned real-world case studies. On the one hand, more jobs will be created to show non-trivial solutions with more vehicles. On the other hand, a toll for large trucks will be introduced.



(a) Plan A: Direct delivery depot → customer

(b) Plan B: Transporting the good depot → hub (left) and hub → customer (right).

Fig. 5: Simulation output: Vehicle routes driven depending on the selected plan.

Table 3: Schedule for the shipment to get transported from the depot to the customer.

(a) Plan A: Direct delivery depot → customer

(b) Plan B: Transporting depot → hub, handling at hub, and delivery depot → customer

		Time [s]				Time [s]	
SolutionElement	Activity	Start	End	SolutionElement	Activity	Start	End
	LOAD	0.0	0.0		LOAD	0.0	0.0
mainCarrier	TRANSPORT	0.0	720.0	mainCarrier	TRANSPORT	0.0	361.0
	UNLOAD	720.0	720.0		UNLOAD	361.0	361.0
				hub	HANDLE	361.0	371.0
					LOAD	370.0	370.0
				distributionCarrier	TRANSPORT	370.0	730.0
					UNLOAD	730.0	730.0

### 5.1. Extended Simulation Experiment — Setup

*Network and Location of the LSP Resources.* The main parts of the setup from the Simple Simulation Experiment (see section 4.1) are also used for the extended simulation experiment: the road network, and the locations of the depot and hub. The number of jobs and the total amount of goods to be delivered from the depot have been changed. A total of ten jobs are randomly created as follows: The customers are randomly placed within the area marked in Fig. 6 — called as inner-city for this study. The demand size requested by each customer (= per job) is also randomly generated in the interval of [1:5].

*Simulation Experiments.* The costs and transport capacities for the logistic solution elements (see Table 1a in Section 4.1) remain unchanged, too. Again, the LSP has the two plans A and B. The most praxis-related setting from the first part of the study is used: Case 3 (Table 1b): Strongly reduced transport costs for the carrier serving the hub → customer delivery, and additional extra costs for using the hub.

In order to reduce the number of large vehicles from the inner-city (see Section 1), an additional cordon toll for the inner-city (see Figure 6) will be introduced. The toll fee is set to 25 Euros. This is far below the values in London for an older HGV entering the London LEZ, which is £300 (approx. 350 €) (Transport for London (TfL), 2022b), and above the daily charge of £12.50 (approx. 14.50 €) for entering the London ULEZ (Transport for London (TfL), 2022b). The new, extended cases and their cost rates are summarized in Table 4.



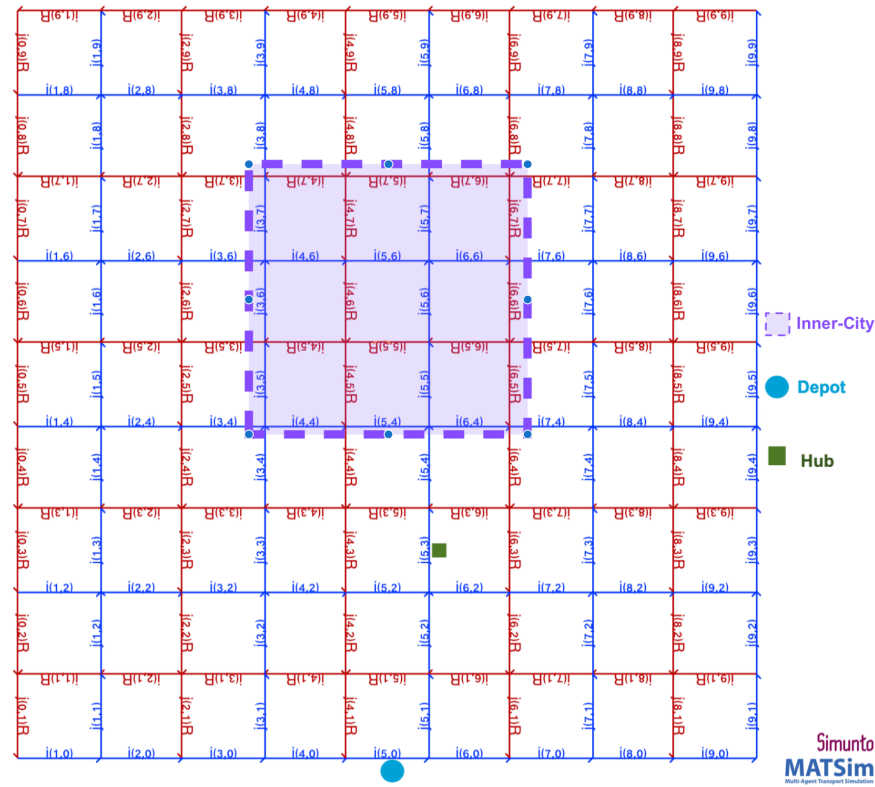


Fig. 6: Extended scenario: The grid network, including the location of the depot (origin), the transshipment hub, and the inner-city zone. Within the inner-city zone, the ten customers (destinations) are placed randomly. The border of the zone is at the same time the border of the additional cordon toll for large vehicles.

Table 4: Parameters for the different simulation setups. The setting is analogous to case 3 in Table 1b). The cost settings (I, II) belong to Table 1a. Deviating, ten different customers located in the inner-city are served. Case 4: Same as case 3, but with ten customers; Case 5: Same as case 4, but with a cordon toll for large vehicles crossing the border to the inner-city zone.

LSP-Plan	Solution	Case 4	Case 5
A	(direct)	I	I
B	depot → hub	I	I
	hub → customer	II	II
	hub [€/day]	100	100
(both)	cordon toll on large vehicles [€]	0	25

### 5.2. Results of the Extended Simulation Experiment

The ten randomly distributed customers have a total demand of 20 units. Figures 7 and 8 show the routes for the two different plans. One can see that, in contrast to the simple scenario, now in both plans several customers are served by one vehicle (tour). Figure 7 shows the solution for plan A, which is the selected one in case 4. The large vehicle is used for all deliveries in a single tour directly from the depot. Figure 8 shows the solution for plan B, which is selected in case 5. The large vehicle is used to transport all goods from the depot to the hub (Figure 8a). For the last-mile delivery, five tours with the small vehicle are planned (see Figure 8b). Due to the one-way network, there is a lot of extra mileage to reach the links of interest.

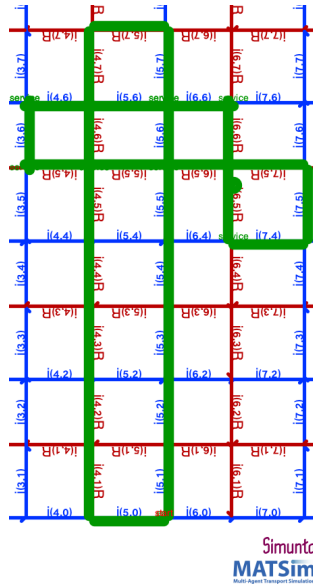
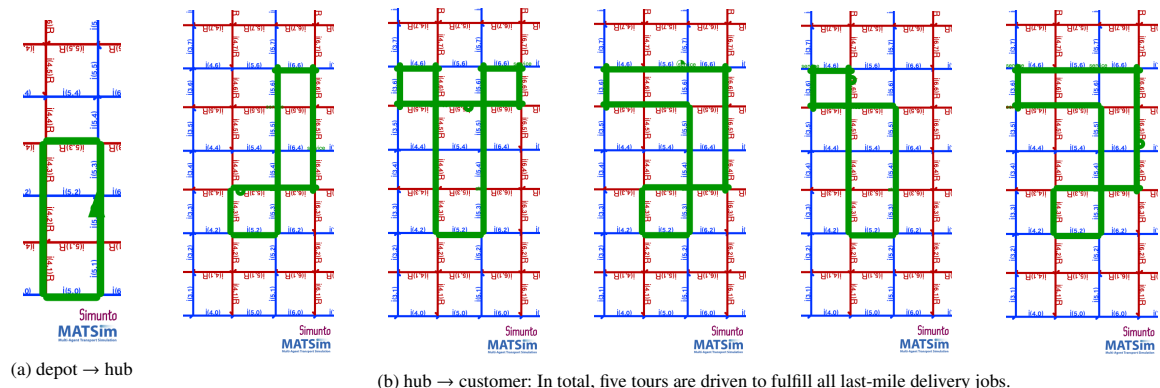


Fig. 7: Simulation output for the extended scenario. Plan A is the selected plan for case 4: Direct delivery of all goods from the depot, using a large vehicle.



(b) hub → customer: In total, five tours are driven to fulfill all last-mile delivery jobs.

Fig. 8: Simulation output for the extended scenario. Plan B is the selected plan for case 5: Using the hub.

The resulting scores and selected plans are summarized in Table 5. It also includes the number of tours for the selected plan and the total mileage driven by all vehicles. Due to the significantly lower vehicle costs, this is the better alternative after implementing the toll for the large vehicles in the inner-city. The reaction of the LSP shows that both the plan execution and, depending on it, the plan selection also work for a non-trivial 2E-VRP. This includes the reaction of the LSP to a vehicle type-specific toll.

## 6. Conclusion and Outlook

In this study, we applied the concept of Logistic Service Providers (LSPs) to an agent-based framework. A LSP is responsible for transporting goods through its logistics network from the origin to the destination. In contrast to previous studies, not only a VRP from the depot to the customer is solved. Instead, it is possible to define a transport chain with transshipment hubs. A LSP can choose between different plans, how it would like to transport the shipments. The decision is based on the score of each plan. In our case, each plan represents an abstract path (solution) for the transport. Abstract means, that it is defined only in terms of the facilities (depot, hubs) used, and the

Table 5: Resulting scores and the by the LSP selected plan for the two additional simulated cases. Depending on the setup (costs for the different plan elements of plan B), a different plan is selected. Plan A: direct delivery; plan B: using transshipment hub.

Plan	Case 4		Case 5	
	A	B	A	B
score	-469.6	-588.9	-494.6	-488.9
selected?	x			x
# of tours	1	-	-	1 + 5
vehicle mileage driven [km]	28	-	-	80

connections (transport by a carrier) between these facilities, as well as from the last facility to the customer. Therefore, different elements in the transport chain have their own behavior, e.g. the distribution carrier, solves its own VRP.

We show, that the plan scoring and selection works as expected. Therefore, we use an artificial grid network scenario. We run three different cases. In all cases, we have one LSP with two different plans: In plan A, the goods are directly transported from the depot to the customer with a large (and more expensive) vehicle. In contrast, plan B has a transshipment hub in between. The three cases differ in the cost structure of the different solution elements. Depending on this setup, either plan A or plan B will be selected by the LSP.

After this proof-of-concept, we extended the simple simulation experiment by introducing i) more shipments and ii) a cordon toll. A total of ten shipments with random destination and random quantity are used. As a result, the last-mile distribution (hub → customer) can only be done with several tours that are planned by the distribution carrier. Again, the LSP chooses the plans as expected: plan A (direct transport) is the better option until an additional toll on large vehicles is introduced. Due to that toll, plan B (using the hub, last-mile delivery with smaller and cheaper vehicles) is the better option.

*Outlook.* Again, this is a proof-of-concept study. The next steps are i) to further increase the computational complexity, e.g. by having different vehicle types per carrier and/or significantly more jobs and customers. It is also planned to run standard instances of the 2E-VRP with our framework for validation. Then we will ii) apply this approach to already existing case studies, e.g., for the supply of supermarkets in a large city such as Berlin, the largest city and capital of Germany. Another possible use case could be the delivery of parcels. As long as we assume that the "direct" delivery will be the cheaper variant (e.g. need for fewer vehicles, no costs for additional hubs, saving on handling costs at the hub), this will be done in conjunction with the introduction of a Low Emission Zone (LEZ) or a ban on large vehicles for certain areas. A even further extension would be to simulate the whole chain including collection run — main run — distribution run, with a Fleet Size and Mix Vehicle Routing Problem (FSMVRP) at each stage.

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