Available online at www.sciencedirect.com

ScienceDirect

Transportation Research Procedia 00 (2023) 000–000

Transportation Research Procedia

www.elsevier.com/locate/procedia

World Conference on Transport Research - WCTR 2023 Montreal 17-21 July 2023

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

Kai Martins-Turner[a,b,*], Kai Nagel[a]

[a]*Technische Universität Berlin, Chair of Transport Systems Planning and Transport Telematics, Straße des 17. Juni 135, 10623 Berlin, Germany*
[b]*Technische Universität Berlin, Chair of Commercial Transport, Straße des 17. Juni 135, 10623 Berlin, Germany*

Abstract

Building up (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 introduce 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. Those decisions need to be done by the Logistic Service Provider (LSP).

In this study, we investigate the behavior of an LSP in an agent-based simulation framework, having different plans: direct delivery, and delivery via a hub. Depending on different input values, e.g. vehicle's fixed and variable costs, or costs for the hub, the LSP make its planning and chooses the plan with the best score. The tour planing on 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 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, like Berlin, Germany.

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

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 participating countries of the 21st session of the Conference of the Parties to the United Nations Framework Convention on Climate Change agreed to limit the 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". This includes the decoupling of the economic growth from resource usage and having zero net GHG-emissions by 2050 (Europäische Kommission, 2019). To achieve this, reducing the transport emissions by 90% until 2050 is one of the aims of the European Commission.

* Kai Martins-Turner, Tel.: +49-30-314-29592 ; fax: +49-30-314-26269
E-mail address: martins-turner@vsp.tu-berlin.de

Different countries also defined their own climate protection plans, e.g. the German "Climate Action Plan 2050" (BMUB, 2016), which foresees the reduction of GHG-emissions of the transport sector by 40% until 2030, compared to 1990. Inside the German transport sector, the road freight transport is responsible for 35% of the CO_2 emissions (BMUB, 2018).

Electrifying the transportation sector could be a suitable solution for achieving these goals, e.g. by replacing the current Internal Combustion Engine Vehicles (ICEVs) by Battery Electric Vehicles (BEVs).

This question is getting discussed more and more because of the changes in urban areas (Caggiani et al., 2020; Oliveira et al., 2020). It starts with the idea to avoid driving with ICEVs into the inner city. Instead, one could replace them by either BEVs or cargo bikes. Because of their limited range / capacity, it is no longer possible to bring the goods directly from the depot to the customers (Ewert et al., 2021; Hiermann et al., 2019) This is leading to a need for local transshipment hubs, for a more local delivery with smaller vehicles. These hubs need the connection to the existing main depots(s). Especially for parcels, the last mile delivery with cargo bikes is expending. Advantages of e-cargo bikes are investigated e.g. by Gruber et al. (2014).

This brings up the question of building up or updating (urban) logistic networks, which is complex. Besides all 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 it be only one tier (direct delivery)? Or is it better to introduce a two-echelon distribution system, transporting the goods with large vehicle to transshipment hubs near to the customers and use smaller, environmentally friendly smaller vehicles for the last-mile distribution (Oliveira et al., 2022)?

Since the range of BEVs is not the major issue anymore, there is a new trend: Ban or charge (large) vehicles not meeting certain requirements from the inner-city: This can be done either for *environmentally reasons*, by introducing a Low Emissions 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 Emissions Zone (ULEZ) with stronger environmental requirements. If not meeting them, a daily charge of 12.50 £ (approx. 14.50 €) must be paid (Transport for London (TfL), 2022c). LEZs prohibiting certain vehicle types from entering areas of a city can be found across other European countries as well: In Germany, e.g. Berlin has introduced a LEZ with the explicit midterm goal to change the operators fleets (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, lorries over 12 tonnes gross vehicle weight are required by the Direct Vision Standard (DVS) and safety permit 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).

As a reaction to this, either significantly more small vehicles are needed to transport the goods from the depots top the customers, or again, a two-echelon distribution network is used. The two-echelon network allows transporting the 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 which are allowed to enter the zone.

The Logistic Service Provider (LSP) [1] is the organizer for the transport chain and the transport of the goods from the sender to the recipient 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 *carrier*s. While the LSP agent organizes the transport chain, the carrier agent is designed to modal a transport operator (Schröder et al., 2012). It plans and models the transportation on individual parts of the transport chain.

1.1. Literature Review

Oliveira et al. (2022) summarize some of the relevant two-echelon Vehicle Routing Problem (2E-VRP) types and their history for 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 done by Perboli et al. (2008). Nevertheless, Crainic

[1] We decided at some point, that we will talk from the 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.

et al. (2004, 2009) are said to be the first addressing the application of the two-echelon distribution systems to the context of city logistics (Oliveira et al., 2022).

Hiermann et al. (2016) choose another approach to face 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 and locations into the actual vehicle routes. Implementations of 2E-VRP with synchronization between vans and bikes are done e.g. by Anderluh et al. (2017, 2019). Wang et al. (2019) proposes the combination of ICEVs on the first and BEVs on 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 delivering the goods directly with e-vans from the depot to the customer, they are using 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 usage of delivers robots on the second tier can save about 70%, up to 90%, of the operational cost compared to the conventional truck-based deliveries. A similar investigation for delivering parcels or small commodities in pedestrian areas or residential clusters by using unmanned vehicles on the second tier is done 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 the delivery robots are transported and dropped off by large vehicles.

2. Materials and Methods

2.1. Software

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).

For simulating freight transport, the extension (contrib) *freight* is available. The freight contrib connects MATSim with jsprit (jsprit) (Zilske and Joubert, 2016; Zilske et al., 2012). Jsprit is an open-source Vehicle Routing Problem (VRP) solver (jsprit, 2018). Jsprit allows the solving of many subtypes of VRPs with e.g. multi-depots, time restrictions, capacity constraint, infinite fleets including Fleet Size and Mix Vehicle Routing Problem (FSMVRP). It bases on iterative approach using the ruin-and-recreate principle from Schrimpf et al. (2000). More information regarding different VRP types can be found in literature, e.g. in Toth and Vigo (2014), Scheuerer (2004) or jsprit (2018). In the conjunction with MATSim it can also solve the VRP basing on a time-dependent road network (see, e.g Martins-Turner et al. (2020); Ewert et al. (2021).

The main limitation is that each VRP only represents one tier of the logistic network. Due to that it is not possible to address 2-echelon problems where one or several transitions hubs may be used between the depot and the customer. There were earlier studies, e.g. Turner (2015), trying to solve that issue, by dividing it into two different subproblems: First the last VRP from the hubs to the customer is solved as a Multi-Depot Vehicle Routing Problem (MDVRP). From that result one can derive the information, how many goods are needed at each hub, which is the input to set up and solve the VRP from the depot(s) to the hub(s).

The new approach using LSPs allows the integrated solving of the whole transportation chain from the depot to the customer. The LSP has the information of the jobs (transport the quantity n of goods from A to B) as well as the infrastructure (depots, hubs) and the carriers for transporting it on the different parts along the logistic network.

Figure 1 shows a small example of such a network. The large vehicle (red) transports the goods from the depot (left) to the hub (green). From there, the last-mile distribution is done by a smaller vehicle (green).

In our agent-based simulation framework, the LSP is the owner of one or several *plans* (Matteis et al., 2019). The behavior of the LSP is analogous to the standard person agents in MATSim: It will select, execute and score one plan per iteration. Figure 2 shows that approach. For the first studies here, and because there is currently no interaction with other agents, the replanning step will only consist of selecting an existing plan.

Each of the different LSP *plans* has at least one *solution* (Matteis et al., 2019). A *solution* is a transport chain from the depot to the customer, including all parts, like the carriers for the transportation or the hub(s) for reloading. Such transport chains can consist of e.g. only of one carrier, soling its own VRP for the direct delivery from the depot to the customer. Or it can be something like a carrier, transporting the goods from the depot to the hub, reload it there and

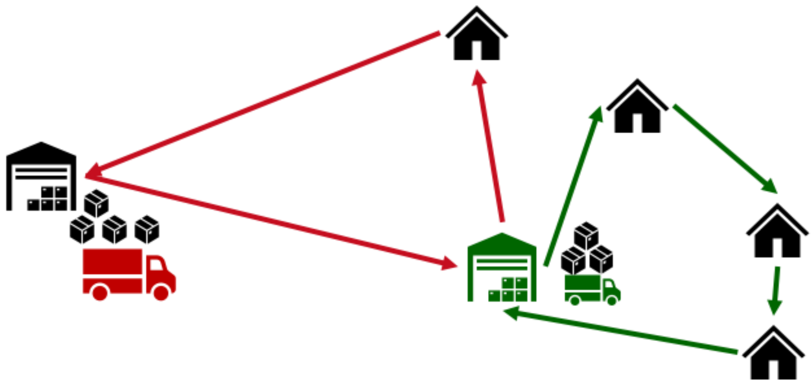


Fig. 1: The two tiers of a two-echelon network

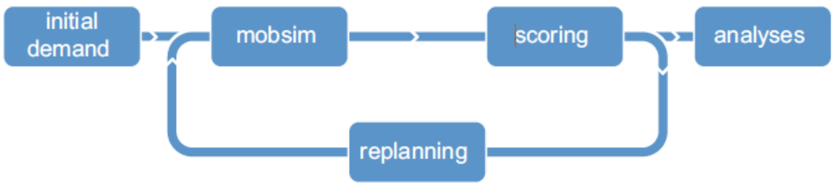


Fig. 2: The MATSim-loop (Source: Horni et al. (2016))

transport it further with (another) distribution carrier. The specific parts of the logistic chain are not planned in detail at this stage: So each carrier will solve its own VRP and decides on the concrete vehicle and tour for transporting the goods.

2.2. Scenario

For this proof-of-concept study, we are using a grid network. The network (see Figure 3) is 9x9 links long. Each link has a length of $l = 1km$ 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 $v = 30km/h = 8.333m/s$, leading to a free speed travel time of $tt_{free} = s/v = \frac{1km}{30km/h} = 120s$. In our study we will have no congestion.

As shown in Figure 3 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 setup follows the description in Sec. 2: It has *two plans* with *one solution* each. 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 two stage delivery: From the depot to the hub and from the hub to the depot. The hub is located at link *j(5,3)*.

3. Trivial Simulation Experiment

As proof-of-concept study, we are running a trivial simulation experiment and observe the decision and result of the LSP.

3.1. Trivial Simulation Experiment - Setup

To show that the LSP will do the right choice and select the better plan as expected, we are running the scenario several times, each with a slightly different setup. In all setups, there is only *one* LSP with *two* different plans. Each plan will only have *one* solution: Plan A with a direct delivery solution, and plan B with a solution using a hub in between. The simulation is run for two iterations, so the LSP will try out and score its both different plans, and then select the better one.

The following cases are considered - see also Table 1 :

1. Same transportation costs for all carriers. This should lead to the selection of plan A, since the costs are lower (= score is higher).
2. Strongly reduced transportation costs for the carrier from the hub to the customer. Because of the significantly lower variable costs for the second stage, plan B has in total the lower costs (= higher score) and thus should be selected.
3. Same as before, but now with extra costs for using the hub. Now again plan A should have the better (higher) score and thus get selected by the LSP.

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

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

3.2. Results for Trivial Simulation Experiment

Table 2 shows the results of all cases. As one can see, the score of plan A (direct delivery) remains constant, because it is the same setup in all cases. The scores of plan B (with hub) differ for the different cases. As described in Table 1 (see Sec. 3), the elements of plan B's solution are modified: For case 2 the costs for the distribution carrier (hub → Customer) are reduced. For case 3 this advantage is overcompensated by taking cost for the hub into account.

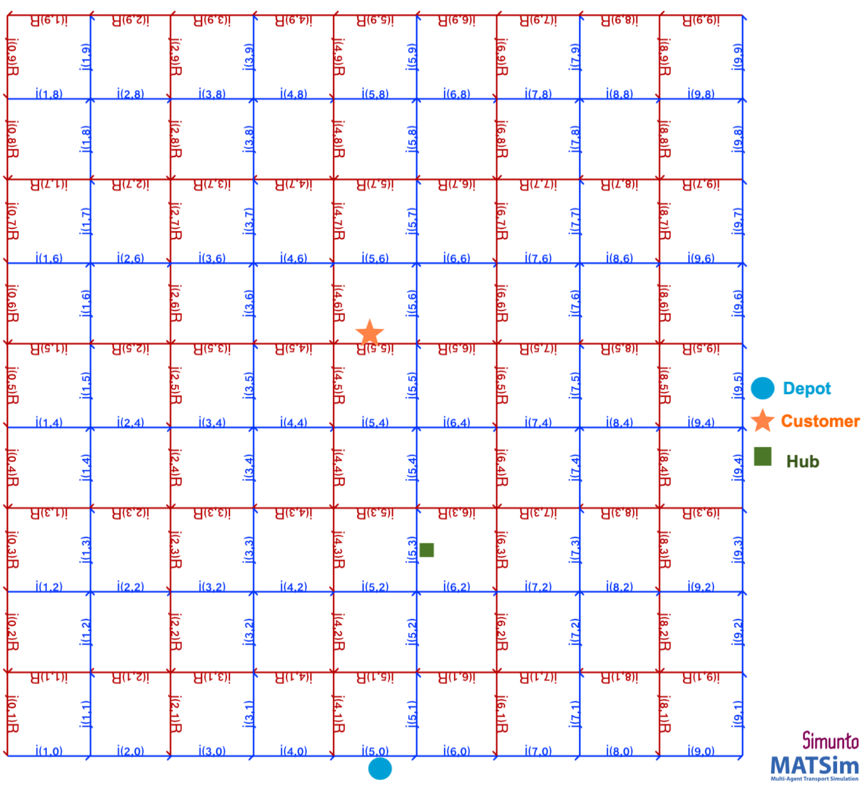


Fig. 3: The grid network, including the location of the depot (origin), the customer (destination) and the transshipment hub. All roads are one-way road. The color indicates the direction: blue: positive direction, red: negative (return) direction

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 from 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

Solution element	Cost type	Value
carrier type I	fixed [€/day]	150
	per distance [€/m]	0.01
	per time [€/s]	0.01
	capacity [units]	50
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

(b) Carrier type usage to the different simulation setups (cases)

LSP-Plan	(solution)	Case 1	Case 2	Case 3
A	(direct)	I	I	I
B	depot → hub	I	I	I
	hub → customer	I	II	II
	hub [€/day]	0	0	100

The scores change accordingly, e.g. the score of plan B is in case 3 compared with case 2 lower by the 100 EUR hub costs.

Table 2: Resulting scores and the (by the LSP) selected plans 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 transshipment hub.

	Case 1		Case 2		Case 3	
Plan	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 smaller are the costs and the plan is *better*. The selected plan is marked with (x). One can see that the LSP selects the *better* plan in all cases.

Figure 4 shows the different routes that the vehicles are driving in the simulation. Figure 4a is the visualization of plan (A), while Figure 4b shows the both segments of the 2-ecehelon 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. Then it is handled in the hub and transported further with the second carrier (distributionCarrier), where it is unloaded at time 730 (see Table 3b).

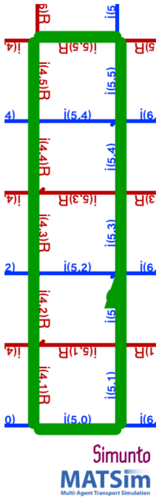
Due to the limited scope and demonstrative nature of this study, the results are rather limited. The plan selection and thus the behavior of the LSP is obviously as expected (see in Sec. sec:simulationSetup)

4. Extended Simulation Experiment

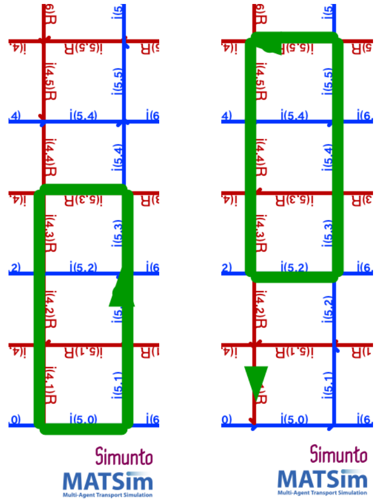
Since we were able to show that the framework works as expected, the scenario is extended towards later planned real-world case studies. On the one hand, more jobs are created, in order to show also non-trivial solutions with more vehicles needed. On the other hand, a toll is introduced for large trucks.

4.1. Extended Simulation Experiment - Setup

The main parts of the scenario from Sec. 2.2 is used for the extended simulation experiment as well: network, depot and hub. The number of jobs and the total amount of goods, that should be delivered from the depot has changed. In



(a) Plan A: Direct delivery depot → customer



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

Fig. 4: 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

		Time [s]	
SolutionElement	Activity	Start	End
	LOAD	0.0	0.0
mainCarrier	TRANSPORT	0.0	720.0
	UNLOAD	720.0	720.0

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

		Time [s]	
SolutionElement	Activity	Start	End
	LOAD	0.0	0.0
mainCarrier	TRANSPORT	0.0	361.0
	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

total, ten jobs are created randomly. The customers were placed randomly within the area marked - called as inner-city for this study - in Fig. 5. The demand size requested by each customer is also randomly drawn in the interval of [1;5].

The costs and transport capacities for the logistic solution elements (see Tab. 1a in Sec. 3) 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 (Tab. 1b): Strongly reduced transportation costs for the carrier serving hub → customer, and additional extra costs for using the hub.

In order to reduce the number of large vehicles from the inner-city (see Sec. 1) an additional cordon toll for the inner-city (see Fig. 5)is introduced. The toll fee is set to 25 Euros, which is far below the values in London for an older HGV entering the London LEZ: 300 £ (approx. 350 €) (Transport for London (TfL), 2022b) and above the daily charge of 12.50 £ (approx. 14.50 €) for entering the ULEZ (Transport for London (TfL), 2022b).

The new, extended cases including their cost rates are summarized in Table 4.

4.2. Results for the Extended Scenario

The ten randomly distributed customer have a total demand of 20 units. Fig. 6 and 7 show the routes for the two different plans. One see, that - in contrast to the simple scenario - now in both plans several customers were served by one vehicle (tour). Fig. 6 shoes the solution for plan A, which is selected in case 4. The large vehicle is used for all deliveries in one tour directly from the depot. Fig. 7 shoes the solution for plan B, which is selected in case 5. The large vehicle is used for transporting the all goods from the depot to the hub (Fig. 7a). For the last-mile delivery, it

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: As case 3, only with ten customers; Case 5: Same as case 4 but a with a cordon toll for large vehicles for driving into 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

takes five tours with the small vehicle (Fig. 7b). Due to the one way network, there is a lot of extra-mileage to reach the links of interest.

The resulting scores and selected plans are now shown in Tab. 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 the toll for the large vehicles is introduced. The reaction of the LSP shows, that both, the plan execution and depending on it the selection works also for a non-trivial 2E-VRP, including the reaction on a vehicle type specific toll.

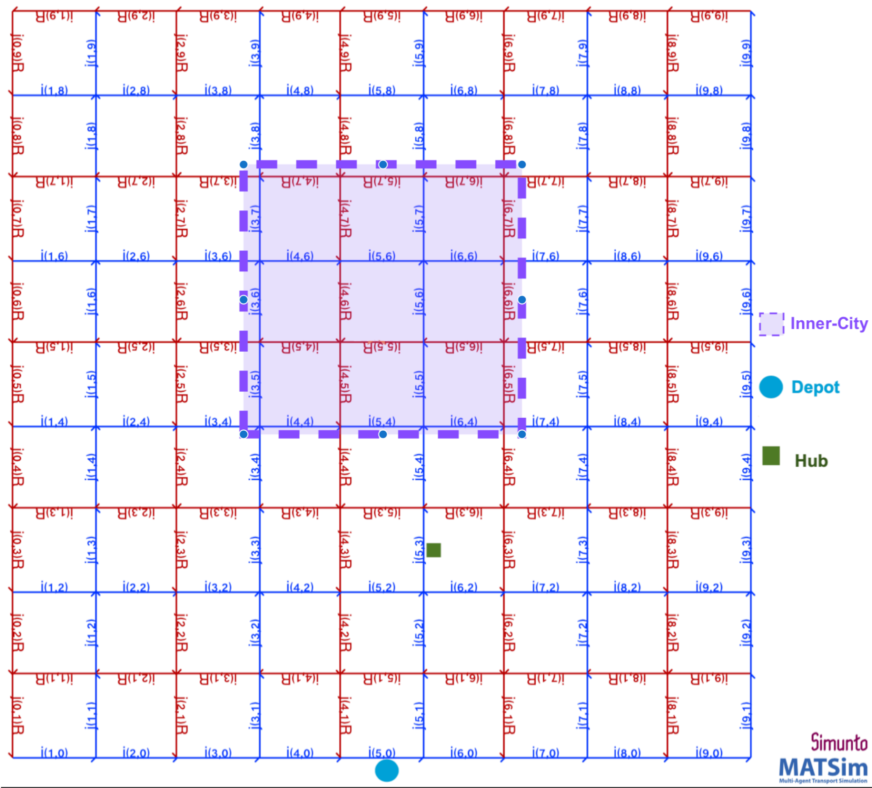


Fig. 5: The grid network, including the location of the depot (origin), the transshipment hub and the inner-city zone. Inside the inner-city zone, the ten customers (destinations) are located randomly. The zone's border is at the same time the border of the additional cordon toll for large vehicle.

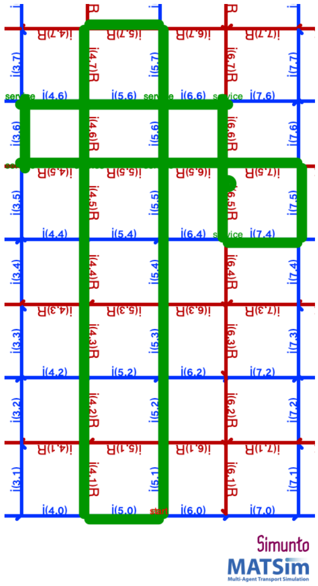
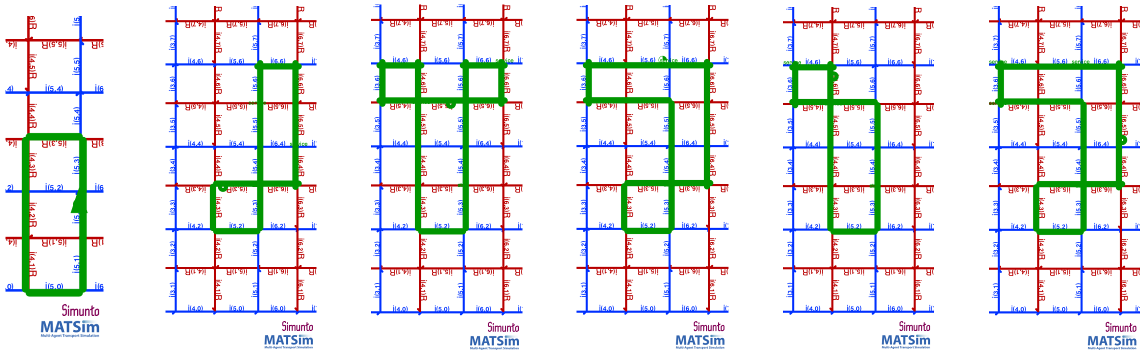


Fig. 6: Simulation output for the extended scenario: plan A is the selected plan for case 4: Direct delivery of all goods from the depot, using a large vehicle.



(a) depot → hub

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

Fig. 7: Simulation output for the extended scenario: plan B is the selected plan for case 5: Using the hub.

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.

	Case 4		Case 5	
Plan	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

5. Conclusion and Outlook

In this study, we applied the concept of Logistic Service Provider (LSP)s to an agent-based framework. A LSPis responsible to transport goods through its logistic network from the origin to the destination. Other than in earlier studies, not only a VRP is solved from the depot to the customer. Instead, it is possible to define a transport chain with transshipment hubs. A LSP can select between different plans, who 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 way (solution) for the transport. Abstract means, that it is only defined in terms of used facilities (depot, hubs) and the 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 has their own behavior, e.g. the distribution carrier, solves his own VRP.

We show, that the plan scoring and selection works as expected. Therefore, we are using an artificial grid scenario. We run three different cases. In all cases, we have one LSP with two different plans: plan A: direct delivery of the goods with a large (and more expensive vehicle), plan B: using 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 is selected by the carrier.

After that proof-of-concept, we extended the trivial simulation experiment by introducing i) more shipments and ii) a cordon toll. In total, 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 small and cheaper vehicles) is the better option.

Outlook. As said, this is a proof-of-concept study. The next steps are i) further extension of the calculation complexity by e.g. having different vehicle types per carrier and/or significantly more jobs and customers. Then we will ii) apply this approach to already existing case studies, e.g. for supplying supermarkets of a large city like Berlin, the largest city and capital of Germany. Another possible usecase could be the delivery of parcels. As long as we are expecting that the "direct" delivery will be the cheaper variant (e.g. need for fewer vehicles, no costs for additional hubs, saving handling costs at the hub), this is done together with the introduction of a Low Emissions Zone (LEZ) or a ban of large vehicles for certain areas. And even further extension would be to simulate the whole chain including collection - main - distribution run, with a Fleet Size and Mix Vehicle Routing Problem (FSMVRP) in each stage.

6. Acknowledgment

This work was funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – 323900421.

References

Anderluh, A., Hemmelmayr, V.C., Nolz, P.C., 2017. Synchronizing vans and cargo bikes in a city distribution network. Central European Journal of Operations Research 25, 345–376. doi:10.1007/s10100-016-0441-z.

Anderluh, A., Nolz, P.C., Hemmelmayr, V.C., Crainic, T.G., 2019. Multi-objective optimization of a two-echelon vehicle routing problem with vehicle synchronization and 'grey zone' customers arising in urban logistics. CIRRELT-2019-33 https://www.cirrelt.ca/documentstravail/cirrelt-2019-33.pdf.

Bakach, I., Campbell, A.M., Ehmke, J.F., 2021. A two-tier urban delivery network with robot-based deliveries. Networks 78, 461–483. doi:doi:10.1002/net.22024.

BMUB, 2016. Climate action plan 2050. http://www.https://www.bmu.de/fileadmin/Daten_BMU/Pools/Broschueren/klimaschutzplan_2050_en_bf.pdf.

BMUB, 2018. Klimaschutz in Zahlen. Fakten, Trends und Impulse deutscher Klimapolitik. Ausgabe 2018.

Boysen, N., Schwerdfeger, S., Weidinger, F., 2018. Scheduling last-mile deliveries with truck-based autonomous robots. European Journal of Operational Research 271, 1085–199. doi:10.1016/j.ejor.2018.05.058.

Caggiani, L., Colovic, A., Prencipe, L.P., Ottomanelli, M., 2020. A green logistics solution for last-mile deliveries considering e-vans and e-cargo bikes. Transportation Research Procedia 52, 75–82. doi:10.1016/j.trpro.2021.01.010.

Crainic, T.G., Ricciardi, N., Storchi, G., 2004. Advanced freight transportation systems for congestedurban areas. Transportation Research Part C: Emerging Technologies 12, 119–137. doi:doi:10.1016/j.trc.2004.07.002.

Crainic, T.G., Ricciardi, N., Storchi, G., 2009. Models for evaluating and planning city logistics transportation systems. Transportation science 43, 432–454. doi:doi:10.1287/trsc.1090.0279.

Europäische Kommission, 2019. Der europäische Grüne Deal. COM(2019) 640 final. COM(2019) 640 final.

Ewert, R., Martins-Turner, K., Thaller, C., Nagel, K., 2021. Using a route-based and vehicle type specific range constraint for improving vehicle routing problems with electric vehicles. Transportation Research Procedia 52, 517–524. doi:https://doi.org/10.1016/j.trpro.2021.01.061.
Gruber, J., Kihm, A., Lenz, B., 2014. A new vehicle for urban freight? An ex-ante evaluation of electric cargo bikes in courier services. Research in Transportation Business & Management 11, 53–62. doi:10.1016/j.rtbm.2014.03.004.
Hiermann, G., Hartl, R.F., Puchinger, J., Vidal, T., 2019. Routing a mix of conventional, plug-in hybrid, and electric vehicle. European Journal of Operational Research 272, 235–248. doi:doi:10.1016/j.ejor.2018.06.025.
Hiermann, G., Puchinger, J., Ropke, S., Hartl, R.F., 2016. The electric fleet size and mix vehicle routing problem with time windows and recharging stations. European Journal of Operational Research 252, 995–1018. doi:10.1016/j.ejor.2016.01.038.
Horni, A., Nagel, K., Axhausen, K.W. (Eds.), 2016. The Multi-Agent Transport Simulation MATSim. Ubiquity, London. doi:10.5334/baw.
jsprit, 2018. https://github.com/graphhopper/jsprit. Accessed on 02-dez-2018.
Martins-Turner, K., Grahle, A., Nagel, K., Göhlich, D., 2020. Electrification of urban freight transport - a case study of the food retailing industry. Procedia Computer Science 170, 757–763. doi:10.1016/j.procs.2020.03.159.
Matteis, T., Wisetjindawat, W., Liedtke, G., 2019. Modelling interactions between freight forwarders and recipients – an extension of the MATSim toolkit, in: 15th World Conference on Transport Research. URL: https://elib.dlr.de/134376/.
Ministère de la transition écologique et de la cohésion des territoires, 2022. URL: https://www.certificat-air.gouv.fr/.
Oliveira, B., Ramos, A., de Sousa, J., 2022. A heuristic for two-echelon urban distribution systems. Transportation Research Procedia 62, 533–540. doi:10.1016/j.trpro.2022.02.066.
Oliveira, B., Ramos, A.G., de Sousa, J.P., 2020. A generic mathematical formulation for two-echelon distribution systems based on mobile depots. Transportation Research Procedia 52, 99–106.
Perboli, G., Tadei, R., Vigo, D., 2008. The two-echelon capacitated vehicle routing problem: Models and math-based heuristics. CIRRELT-2008-55 .
Scheuerer, S., 2004. Neue Tabusuche-Heuristiken für die logistische Tourenplanung bei restringierendem Anhängereinsatz, mehreren Depots und Planungsperioden. phdthesis. Universität Regensburg. URL: https://epub.uni-regensburg.de/10196/.
Schrimpf, G., Schneider, J., Stamm-Wilbrandt, H., Dueck, G., 2000. Record breaking optimization results using the ruin and recreate principle. Journal of Computational Physics 159, 139–171. doi:10.1006/jcph.1999.6413.
Schröder, S., Zilske, M., Liedtke, G., Nagel, K., 2012. Towards a multi-agent logistics and commercial transport model: The transport service provider's view. Procedia Social and Behavioral Sciences 39, 649–663. doi:10.1016/j.sbspro.2012.03.137.
Senatsverwaltung für Umwelt, Verkehr und Klimaschutz Berlin (SenUVK), 2017. Umweltzone - bessere Luft für Berlin. see https://www.berlin.de/senuvk/umwelt/luftqualitaet/umweltzone/download/umweltzone_flyer_2017.pdf.
Toth, P., Vigo, D. (Eds.), 2014. Vehicle routing: problems, methods, and applications. Society for Industrial and Applied Mathematics (SIAM). doi:10.1137/1.9781611973594.
Transport for London (TfL), 2022a. Direct Vision Standard and HGV Safety Permit. URL: https://tfl.gov.uk/info-for/deliveries-in-london/delivering-safely/direct-vision-in-heavy-goods-vehicles#on-this-page-0.
Transport for London (TfL), 2022b. Lorries, coaches and larger vehicles over 3.5 tonnes. URL: https://tfl.gov.uk/modes/driving/ultra-low-emission-zone/larger-vehicles.
Transport for London (TfL), 2022c. ULEZ: Where and when. URL: https://tfl.gov.uk/modes/driving/ultra-low-emission-zone/ulez-where-and-when.
Turner, K., 2015. Agenten-basierte Modellierung und Simulation von Tourenplanung im städtischen Güterverkehr. Master's thesis. TU Berlin.
United Nations, 2015a. Paris agreement. URL: https://treaties.un.org/pages/ViewDetails.aspx?src=TREATY&mtdsg_no=XXVII-7-d&chapter=27&clang=_en.
United Nations, 2015b. Transforming our world: the 2030 Agenda for Sustainable Development. https://sdgs.un.org/sites/default/files/publications/21252030\Agenda\for\SustainableDevelopment\web.pdf.
Wang, D., Zhou, H., Feng, R., 2019. A two-echelon vehicle routing problem involving electric vehicles with time windows. Journal of Physics: Conference Series 1324. doi:10.1088/1742-6596/1324/1/012071.
Yu, S., Puchinger, J., Sun, S., 2020. Two-echelon urban deliveries using autonomous vehicles. Transportation Research Part E: Logistics and Transportation Review 141. doi:10.1016/j.tre.2020.102018.
Zilske, M., Joubert, J.W., 2016. Freight traffic, in: Horni et al. (2016). chapter 24. doi:10.5334/baw.
Zilske, M., Schröder, S., Nagel, K., Liedtke, G., 2012. Adding freight traffic to MATSim. VSP Working Paper 12-02. TU Berlin, Transport Systems Planning and Transport Telematics. URL http://www.vsp.tu-berlin.de/publications.