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Modeling framework for the agent-based simulation of rail-based urban parcel transport: An application of a two-stage transport chain selection model in the city of Karlsruhe, Germany

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ABSTRACT

In recent years, innovative city logistic concepts for courier, express, and parcel (CEP) shipments have raised particular interest in contributing to a more sustainable transportation system. One solution can be the utilization of existing urban rail infrastructure. A so-called 'cargo tram' transports goods to an intermodal city hub, where cargo bikes cover the last leg to the receiver. Although conceptional or economic studies exist, detailed analyses of the transport-related effects, e.g., through freight demand models, still need to be carried out. Hence, in this study, we develop a methodology to integrate urban rail-based parcel transport in terms of a cargo tram into the existing agent-based freight, i.e., parcel, demand model *logiTopp*. Instead of a single mode choice, a two-stage selection model based on transport chains is developed, comprising a rule-based and utility-based stage. The proposed methodology is implemented in *logiTopp*, and the model is applied to the city of Karlsruhe, Germany, where the overall effects of rail-based parcel transport are simulated and evaluated in proof-of-concept scenarios. The analysis shows that the proposed transport chain selection model produces overall reasonable results. Moreover, they indicate that the realization of a rail-based parcel transport can reduce the overall mileage and number of trips caused by CEP shipments. However, the potential is driven by several factors, such as the number and location of city hubs, the maximum range of cargo bikes, and the overall evaluation of the cargo tram. Additional empirical investigations are necessary to validate the results from the proof-of-concept scenarios.

1. Introduction

Due to the decline in local trade and the substantial increase in the e-commerce business, a massive growth in the number of parcels shipped by traders to their customers can be observed for several years. The Covid-19 pandemic has further strengthened this development, and the growth trends are not expected to stop. Urban areas already suffer increasingly from the congestion of road infrastructure, space problems in general, as well as increasing traffic emissions and thus decreasing quality of life for citizens. Thus, especially for those areas, this development leads to an increasing burden. In order to avoid that courier, express, and parcel service providers (CEPSP) simply expand the number of their vehicles to respond to the rising parcel demand, urban planners are looking for new solutions for sustainable city logistic concepts. These aim to reduce the growing externalities caused by courier, express, and parcel (CEP) shipments on the overall transportation system.

An important goal for sustainable city logistics is to reduce the ton-kilometers of goods transported or to shift to 'city-friendly' vehicles. Traditional regulatory measures such as the introduction of parking space management or access restrictions have not yet solved the existing and growing problems (Crainic et al., 2004). A promising solution is the establishment of so-called city hubs, which are intended to act as intermediate depots for parcels close to the city center between the distribution center outside the city and the recipient of the parcels. Vehicles with higher capacity are to be used on the route between the distribution center and the city hub, thus enabling more efficient logistics. One such vehicle could be a so-called cargo tram. As the urban rail infrastructure

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already exists and trams are installed with fixed timetables in many cities worldwide, this solution seems promising for more sustainable city logistics. A city hub would work as an intermodal handover point in that case. This is the functionality literature suggests being the most beneficial according to the goals of city logistics (Groothedde et al., 2005; Reis & Macário, 2019). The fine distribution from the city hub to the customer will be carried out using smaller, environmentally friendly vehicles such as cargo bikes.

While the idea of a cargo tram delivery is not new, the investigation of the transport-related effects of such a city logistic concept are still unclear. Existing studies evaluating the effectiveness of a cargo tram system are either qualitative in nature (Strale, 2014) or, in the case of quantitative studies, have a solid economic focus, e.g., cost-benefit analyses (De Langhe et al., 2019), monetizing transport-related effects only in rough projections. Detailed analyses of the transport-related effects, e.g., through freight demand models, still don't exist. Hence, with this study, we want to close this research gap and develop a methodology to integrate the urban rail-based parcel transportation concept via cargo trams in an agent-based, disaggregated freight demand model. More precisely, we refer to the agent-based travel demand model (TDM) *mobiTopp* and its logistical extension *logiTopp* as modeling environment. The integration of a cargo tram as a new mode for CEP-based shipments goes along with the modeling of transport chains, as the cargo tram only works as an intermodal shipment solution. Therefore, we develop a two-stage transport chain selection model comprising a rule-based and a utility-based stage, which also reflects all relevant transport chains without a cargo tram. Hereby, a comprehensive analysis of the transport-related effects of supplementary urban rail-based parcel shipments is guaranteed. The developed methodology is integrated into the *logiTopp* model, and the results are evaluated as a proof-of-concept at the example of the city of Karlsruhe, Germany.

This paper is organized as follows. First, we provide an overview of the current research on cargo tram systems, relevant literature on freight demand models, and an outlook on the vehicle routing problem. Second, we give an overview of the agent-based TDM *mobiTopp* and its logistical extension *logiTopp*, as well as their necessary extensions for the study at hand. Third, the concept, development, and implementation of the two-stage transport chain selection model are explained. Fourth, we introduce scenarios for cargo tram-based parcel transportation and present the results we gained from the implementation in the modeling framework *logiTopp* as a proof-of-concept. Finally, we give a conclusion.

2. Literature review

Given the rapidly increasing volume of shipments, e.g., due to e-commerce, the analysis of mode choice, and hereby, innovative solutions in freight transport received significant interest from researchers. In particular, the shift to environmentally friendly modes has become the goal of many research projects, even if it is only for a part of the total transport distance. As outlined in the introduction, cargo trams are such a promising approach for first and last mile shipments to reduce urban road traffic (Behiri et al., 2018), leveraging the environmentally friendly rail-based transport system for urban freight delivery (Nemoto et al., 2006). The basic idea is the utilization of passengers' unused capacity in public transit for freight transport (De Langhe et al., 2019; Van Duin et al., 2019). According to De Langhe et al. (2019), three operational modes can be differentiated: dedicated freight vehicles using the existing urban rail infrastructure, freight wagons coupled with passenger vehicles, and freight transport within existing passenger vehicles.

European cities have already implemented cargo tram systems or tested variations in pilot projects. Most of those projects are based on dedicated vehicles for freight transport, such as pilots in Paris, Amsterdam, Dresden, Zurich, Frankfurt, and Vienna (APUR, 2011; Cleophas et al., 2019; Gonzalez-Feliu, 2016). However, dedicated trams require additional resources, e.g., freight vehicles. Furthermore, its success depends on available urban rail network capacities, which are typically low due to the high frequencies of passenger trams. Systems in which freight wagons are coupled with passenger vehicles are scarce and haven't been realized yet. Nevertheless, conceptional studies, e.g., on the operating strategies at the example of the Toronto area, Canada, reveal that the current public transit networks in urban areas suffer from available rail capacity to realize such a system (Cochrane et al., 2017).

Research on combined freight and passenger transport within the same vehicles is scarce as well (Pimentel & Alvelos, 2018). Pilot studies have been initiated just recently, for example, in Karlsruhe, Germany, (AVG, 2021) or Strasbourg, France (ALSTOM, 2024). In contrast to both other operational modes, combined freight and passenger transport within the same rail vehicle utilizes existing transport capacities while conserving resources. Some studies such as Bektaş et al. (2017) expect an economically attractive operation with reduced personnel costs for the combined transport. However, the operational challenges remain striking through the full integration in the passenger transport. These are mainly caused by restricted time windows for loading and unloading processes, which are typically carried out manually (Arvidsson & Browne, 2013; Schocke et al., 2019). Therefore, recent projects such as the pilot in Karlsruhe, Germany, aim to incorporate automated handling technologies to ensure compliance with the originally planned stopping times, and, thereby, reducing labor costs and enhancing transshipment efficiency, both being critical to the performance of a cargo tram (Regue & Bristow, 2013).

In summary, pilots and conceptional studies indicate that cargo trams can be effective if factors such as transported volume, road transport efficiency, timing, post-haulage needs, and operational costs are carefully considered. Still, the socio-economic benefits generally outweigh the business-economic ones (De Langhe et al., 2019). However, the analysis of a cargo tram's transport-related effects as part of the socio-economic benefits remains disregarded, such as in Strale (2014), or is based on a simplistic evaluation considering aggregated key figures, such as in De Langhe et al. (2019) or Van Duin et al. (2019). Although a variety of disaggregated freight modeling frameworks have already been proposed in the literature, the transport-related effectiveness of a cargo tram concept has not yet been evaluated and analyzed in any of those. As mentioned before, a cargo tram solution requires the depiction of the mode choice as a transport chain decision because it only works as an intermodal shipment solution. For national to regional freight demand models, transport chain models considering logistical decisions have been presented in the literature, as shown in the following.

The 'aggregate-disaggregate-aggregate model' (ADA) can be used at different geographic levels (national to regional) for forecasting freight transport and its impacts. An aggregated set of good flows gets disaggregated into firm-to-firm flows to model the choice of shipment size and its transport chain afterward. The selection of the transport chain, including distribution centers and transport modes, is done by minimizing the annual logistics costs, resulting in a discrete choice model with logit distribution (Ben-Akiva & de Jong, 2013).

Considering different transport modes, such as road, rail, combined transport of road and rail, etc., Spahn and Lenz (2007) developed a mode choice model for freight transport embedded in the multi-level freight transport demand model WiVSim. The choice of transport modes is a combination of a rule-based and discrete choice model based on the parameters of goods category, transport distance, transport cost, lot size, and distance to highway exits and access points to rail, ship, and air modes. While the rule-based model determines the availability of each transport mode for the respective good, the discrete choice model performs the concrete choice of transport mode.

In the agent-based transportation and production simulator (TAPAS), the modeling of individual actors of a transport chain, such as producers, transport operators, and customers, is performed explicitly. The decision on the transport chain choice results as the solution to a problem of the shortest path whose edges are weighted by the transportation costs between the shipper, receiver, and (possible) intermediate nodes. These costs are composed of time-based costs (e.g., driver, capital, and administration), distance-based costs (e.g., fuel, vehicle wear, and kilometer tax), and link-based costs (e.g., road tolls) (Davidsson et al., 2008; Holmgren et al., 2007).

However, cargo trams work as an urban shipment solution for the first and last mile. A transfer of existing transport chain modeling techniques in national or regional models to urban freight models has not been done yet, and mode choice in urban freight models is still reflected as a single choice of one distinct mode. For example, one of the first urban freight models (GoodTrip) introduced by Boerkamps et al. (2000) determines a single mode choice for each OD (origin-destination) pair primarily based on the origin of the goods and incorporating vehicle capacity, capacity utilization, and the number of stops.

To assess city logistics measures, Nuzzolo and Comi (2014) present an agent-based urban freight model comprising three model sub-systems estimating the quantity OD matrices by transport service type, the delivery OD matrices by delivery time, and the vehicle OD matrices. The latter considers several aspects of logistics operations, such as the number of deliveries per tour, departure time, vehicle type, and delivery locations, but considers only one vehicle type per delivery tour.

More recent models, such as MASS-GT (de Bok et al., 2022; de Bok & Tavasszy, 2018), assign each shipment to one vehicle type depending on the transported goods type and according to a probability distribution derived from a large dataset with observed freight transport data for the Netherlands. For each vehicle, shipments get assigned sequentially with regard to vehicle capacity and its current utilization degree. In the urban freight model SimMobilityFreight (Sakai et al., 2020), shipment sizes are determined based on multinomial logit models, allocated to one supplier, and, as part of the vehicle operations planning, assigned to a distinct vehicle. A similar assignment process is implemented in CRISTAL (Stinson & Mohammadian, 2022), where shipments are allocated to one distinct vehicle, but no intermodal transport chains on the first and last mile are considered.

To model the decision-making behavior of freight operators realistically, the vehicle routing problem (VRP) for distribution logistics, stemming from the operations research literature, has to be addressed. The goal is to achieve a high delivery performance with the given vehicle fleet and capacity by minimizing the related costs. These costs can be further separated into internal (e.g., operational costs, such as fleet and fuel costs) and external costs (e.g., due to polluting emissions). Depending on the selected performance and cost factors, which transform into constraints and variables of the problem, different variants of the VRP exist (Konstantakopoulos, Gayialis, & Kechagias, 2022).

In this context, some approaches to city logistics deal with optimized routing algorithms, such as the cluster-first route-second algorithm, including additional depots (e.g., city hubs) and intermodal transport chains (Jesus Gonzalez-Feliu and Josep-Maria Salanova Grau, 2015). The so-called city-VRPs also comprise access restrictions and other environmental protection measures, which, in practice, usually lead to the use of smaller, more environmentally friendly distribution vehicles in cities. Analogously, this results in city hubs, which get incorporated into multi-level VRPs considering several layers of consolidation and delivery. Depending on the number of levels, these VRPs are classified as two-echelon or multi-echelon VRPs (Gayialis et al., 2019). Perboli et al. (2011) propose a 'two-echelon capacitated VRP' for the city logistics approach in which each level is considered sequentially. Such levels are, for example, the connections between a peri-urban distribution center and city hubs and the connections between the city hubs and the receivers.

Based on the literature review, the challenge of the research effort in this study can be summarized into three major aspects. First, a methodology for modeling transport chain decisions in urban freight demand models needs to be developed, enabling the simulation of a cargo tram solution as part of city logistics. Second, as most recent cargo tram pilots, such as in Karlsruhe or Strasbourg, plan with a combined freight and passenger transport within the same tram vehicle, the investigation has to focus on that particular operational mode, also due to its negligence in existing literature. Third, the focus lies on modeling the freight operators' decision behavior for intermodal transport chains as feasibly and realistically as possible. As seen above, most models, rather than modeling the decision-making of individual firms, rely on available statistics to infer the utility functions, generally in the form of binomial or multinomial logit models, of each operator.

3. Modeling framework

3.1. Agent-based travel and freight demand modeling framework

For our work, we use the agent-based travel demand modeling framework *mobiTopp* (Kübler & Briem, 2022; Mallig et al., 2013; Mallig & Vortisch, 2017). It consists of two modules: a long-term and a short-term module. In the long-term module, a synthetic population is generated for the survey area by drawing households and their members from a population pool and matching it with the regions' general sociodemographic statistics. Each person is assigned mobility tools like a driver's license, public transit ticket, or membership to mobility providers, as well as an activity schedule for the period of one week (Hilgert et al., 2017). In the short-term module, these activities and the intermediate trips are simulated simultaneously for all agents. Before each trip, the choice of destination and mode of transportation is modeled using discrete choice models.

In previous work, we extended the *mobiTopp* framework by a logistics module called *logiTopp* (Kübler & Briem, 2022; Reiffer et al., 2021). It allows to simulate the travel demand generated by last-mile parcel deliveries. *logiTopp* first estimates the weekly parcel demand for each potential recipient: either private persons or establishments located in the survey area. The parcel demand model estimates the parcel quantity as well as additional parcel attributes like the arrival day (based on a weekly distribution), the delivery type (home, work, parcel locker; logit-based), and the CEPSP and a distribution center (based on market shares). Reiffer et al. (2023) present a parcel demand model for private agents and Barthelmes et al. (2023) provide an approach for establishment agents with advanced modeling features such as carrier contracts (Kübler et al., 2023). The parcel demand is determined in the long-term module before the last-mile delivery simulation.

In the short-term module, private agents and delivery agents (as well as CEPSPs and their distribution centers) are simulated simultaneously. Every distribution center owns its own fleet, which can contain vehicles of two types: light-duty vehicles (LDV) and cargo bikes. However, the last-mile delivery simulation only uses a single mode of transportation per parcel. Delivery chains using multiple vehicles are not yet supported but is extended in the paper at hand. The vehicles' capacity (in terms of the number of parcels) is drawn from a normal distribution to account for varying parcel sizes. However, currently, no dedicated mode choice takes place. At the beginning of the simulation period, whether light-duty vehicles or cargo bikes are used, is fixed.

The delivery process starts when a delivery agent arrives at a distribution center and starts the work activity. Here, they are assigned to a delivery tour, which is a sequence of delivery stops for nearby households and establishments. To plan the delivery tours, each CEPSP can apply a unique tour planning strategy. By default, a route-first cluster-second heuristic is applied. After assigning the tour, the delivery agent executes the delivery activities in the planned order. In this way, *logiTopp* simulates the last mile directly from the distribution center to the recipient. Due to the simultaneous, agent-based simulation of private, establishment, and delivery agents, it is possible to model agent-agent interactions at the time of delivery.

3.2. Relevant extensions of logitopp

For the integration of an urban rail-based parcel transport into the *logiTopp* framework, additional functionalities had to be integrated, going along with the collection of additional data.

Currently, *logiTopp* only considers a standardized parcel as a unique unit. However, as the integration of urban rail-based parcel transport goes along with the delivery via transport chains, where different modes with different transportation capacities are involved, the assumption of a unique parcel size cannot be held anymore. Hence, in the first step, we introduced the new parcel attribute 'shipment size' to account for varying parcel volumes, resulting in different parcel loads for vehicles with the same fixed volume capacity. Hereby, we based our assessment on the information provided by the market leader in the German CEP market, DHL, which accounts for almost 50 % of all parcel deliveries (Pitney Bowes, 2022). In expert interviews with CEPSPs in Germany presented in Barthelmes et al. (2024), it was found that the structure of DHL parcel lockers roughly reflects the size distribution of all parcels shipped by DHL. For this reason, we counted the number of compartments in the corresponding size classes small (S), medium (M), large (L), and extra large (XL) at a total of 14 parcel lockers within the study area of the present work. The distribution of the number of compartments per parcel size varies only by a few percentage points throughout all parcel stations. The average values are shown in Table 1. In addition, each parcel was assigned a volume based on the dimensions of parcels within the corresponding size category. The sizes are also shown in Table 1.

Based on those empirical results, the newly introduced 'shipment size' attribute in *logiTopp* supports four different shipment sizes for parcels: small, medium, large, and extra large. The shipment size attribute is determined in the parcel demand model along with the other parcel attributes. Here, we apply a model that meets the overall parcel size distribution presented in Table 1.

Additionally, we introduced the new mode 'cargo tram' into *logiTopp*. It follows a fixed schedule with departure and arrival times according to the existing public transit timetables. The departure times specify when CEPSPs need to load their parcels onto the tram at their respective station. The arrival times define when these parcels are unloaded at the city hubs. After arriving at the city hubs, the parcels are available for transportation via cargo bike. Hence, this extension allows the simulation of transport chains with multiple modes.

4. Concept

The investigation of the transport-related effects of a supplementary rail-based urban parcel transport requires an additional modeling effort exceeding the existing functionality of established urban freight demand models. In contrast to the currently implemented logistical mode choice, e.g., in *logiTopp*, where a parcel is transported from a CEPSP's distribution center to the recipient, whether exclusively by light-duty vehicles or by cargo bikes, urban rail-based transportation requires a more complex transport chain. The so-called cargo tram can only transport goods where rail infrastructure is available. Hence, an exclusive shipment of goods directly to and from recipients is impossible. However, existing concepts of urban rail-based freight transportation always presume the existence of city hubs that are close to a tram stop. These hubs are used to transship and handover the goods from the tram to another mode, typically cargo bikes, before they are delivered to the recipient. As the so-called 'last mile' is composed of at least two legs in that concept, the last leg with a cargo bike or others is also called the 'very last mile', or 'very first mile' for the first leg, respectively, when goods are picked up from a CEPSP. For logistical reasons, goods delivered via such a multi-leg transport chain must already be loaded at the CEPSP's distribution center in that transport vessel which is also used for delivery on the very last mile. In this way, unnecessary reloading of the goods, and thus high costs, can be avoided. However, integrating this type of shipping into an urban freight demand model means that the choice of transport mode must already be made at the distribution center for the entire transport chain on the (very) last/first mile. Accordingly, no new decision is made when changing the mode of transport at the city hub, which is in line with comparable approaches in national or regional freight demand models presented in the literature.

Table 1
Distribution of parcel sizes and corresponding volumes.

Size Class	Relative quantity	Dimensions	Volume
S	41 %	25 cm × 17.5 cm × 10 cm	4.4 l
M	43 %	37.5 cm × 30 cm × 13.5 cm	15.2 l
L	13 %	45 cm × 35 cm × 20 cm	31.5 l
XL	3 %	120 cm × 60 cm × 60 cm	432.0 l

In the following subsections, we present a methodology that integrates the option of urban rail-based goods transportation in terms of a cargo tram shipment, and hence multi-leg transport chain selection, in the existing mode choice model of *logiTopp*, where up-to-date goods are transported exclusively by one mode. First, we define relevant transport chains that are considered within the model. Second, the developed method is explained in detail. Hereby, a two-stage procedure is applied, consisting of a *rule-based decision model* in the first stage and a *utility-based decision model* in the second stage. Furthermore, we show the necessary adoptions within the modeling framework due to the proposed procedure.

4.1. Transport chain options

The consideration of a cargo tram as a new mode of transport on the first/last mile and the related installation of city hubs at designated stops of the cargo tram enables new possibilities for transport chains, not only for transport chains involving the cargo tram itself but also for other modes. Fig. 1 shows all relevant transport chains considered in the further modeling process. Each transport chain starts at a CEPSP's distribution center and ends at a recipient, which can be a private person or an establishment, according to *logiTopp's* current implementation. However, the return direction for the first mile is also considered, even if the following descriptions refer to the direction of the last mile. Moreover, different transport chains for different parcels can be used from each distribution center.

Transport chain A in Fig. 1 illustrates the direct delivery of parcels using a light-duty vehicle, which corresponds with the status quo in *logiTopp* and other urban freight demand models. Parcels are packed in a light-duty vehicle at the CEPSP's distribution center and delivered to the corresponding recipients within a vehicle's tour. Structurally the same, but instead of light duty vehicles, cargo bikes are used in transport chain B, which is also an already possible mode in *logiTopp*. However, transport chain C is the first one representing a multi-leg delivery process on the last mile. Similar to option A, parcels are packed in a light-duty vehicle at the CEPSP's distribution center but are transported to a city hub. From there, parcels are transferred to cargo bikes and delivered to the corresponding recipients within designated tours. Theoretically, cargo bikes could also be used on the first leg and light-duty vehicles on the second leg. However, this option would not be implemented in practice due to logistical reasons, and hence, is not considered in the following. Transport chains reflecting the cargo tram are illustrated in options D and E in Fig. 1. In transport chain option D, parcels are packed directly onto the cargo tram and transported to the city hub. Parallel to option C, parcels are transferred to cargo bikes at the city hubs and delivered to the recipients. As this option requires direct access of a CEPSP's distribution center to rail infrastructure, which only applies to few CEPSPs, transport chain option E is important to consider. Parcels are packed in light-duty vehicles and transported to a CEPSP's closest tram station, where the parcels are turned over to the cargo tram. From that point, option E is the same as transport chain D.

4.2. Two-stage transport chain selection model

Considering a possible methodology to model the previously introduced transport chains within the *logiTopp* framework, several challenges have to be overcome. First, a cargo tram is a public mode of

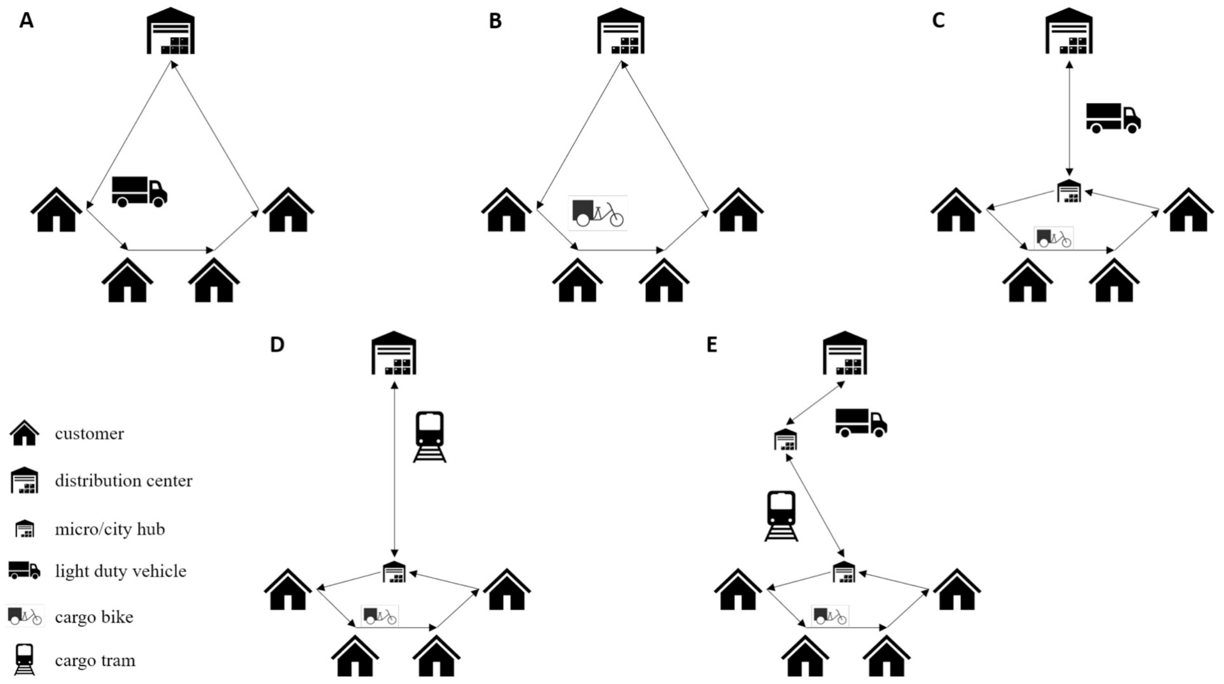


Fig. 1. Relevant transport chain options for consideration of rail-based last/first mile delivery.

transportation usable by all CEPSPs, and not exclusively by only one CEPSP, which is mostly the case, for example, for light-duty vehicles. Therefore, one requirement for the methodology to be developed is that it represents a global decision-making behavior and does not reflect the decision behavior exclusively of individual CEPSPs. Furthermore, it has to be regarded that a cargo tram is a mode of transport that has not yet been established or realized. Hence, the individual parameters influencing the decision to choose the transport with a cargo tram are still mostly unknown. Therefore, the requirement arises to reduce a transport chain selection model, which integrates a cargo tram, to the basic established decision variables in logistics, such as time and costs. Moreover, the representation of all possible transport chains in Fig. 1 shows that when using a cargo tram, cargo bikes are always used on the very last mile. Compared to light-duty vehicles or the cargo tram itself, cargo bikes have additional restrictions regarding the type of goods to be transported as well as the possible delivery areas. Therefore, another requirement of a transport chain selection model is to check a good's suitability for using each mode within the transport chain, whereas the mode with the strongest restrictions has to dominate the decision of whether a good can be shipped via that transport chain or a less restrictive option has to be chosen. In order to meet these requirements, we developed a two-stage transport chain selection model, incorporating a *rule-based* in the first and a *utility-based decision model* in the second stage, which are explained in more detail in the following subsections.

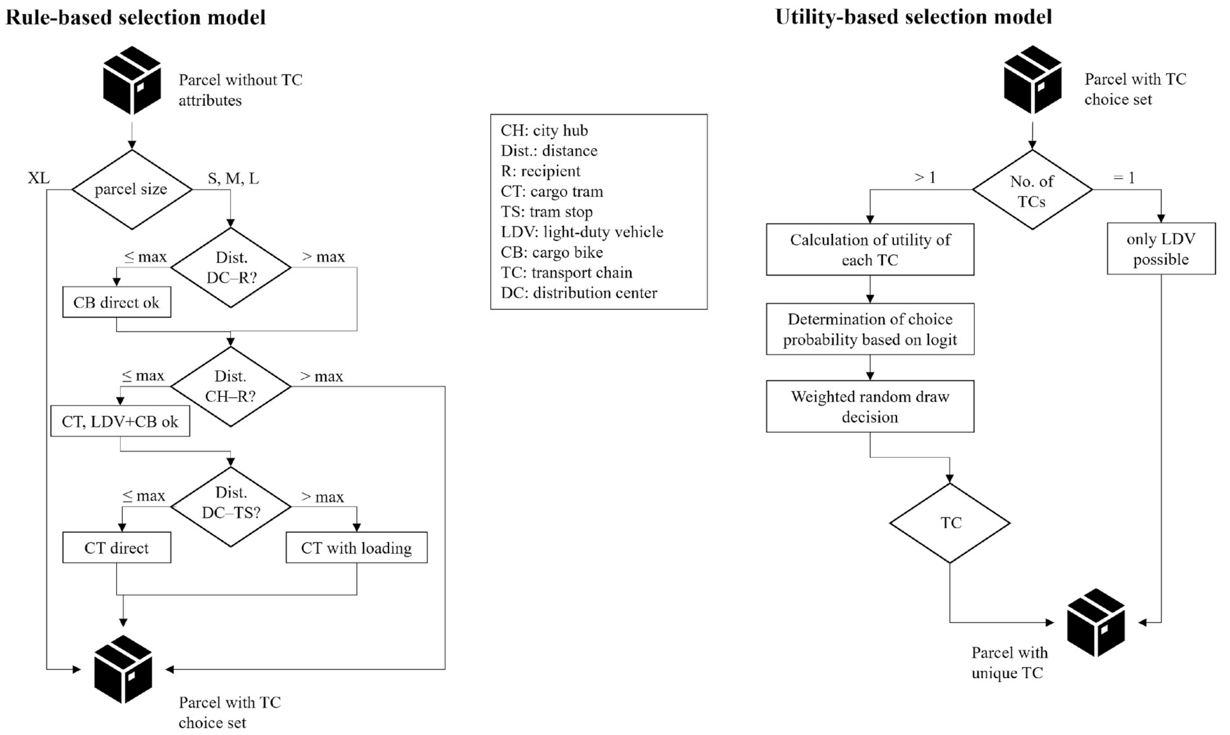
4.2.1. *Rule-based transport chain selection*

The *rule-based* stage addresses the requirement that not all parcels are suitable to be shipped via transport chains incorporating cargo bikes, as these are limited in their capacity and delivery range. Hence, the considered rules are based on a parcel's size (as presented in Section 3.2), reflecting the capacity restriction, and the distance between a parcel's destination and distribution center, reflecting the delivery range restriction, respectively. The procedure is similar to the WiVSim model (Spahn & Lenz, 2007), which also precedes the actual freight mode choice with a rule-based decision to avoid unsuitable mode options in the subsequent selection model. That scheme also shows parallels to the passenger transport modeling such as mobiTopp, where, e.g., agents only can select the car if they have a driver's license. Thus also, a logical check takes place before the actual mode choice.

The realization of the rule-based stage of the transport chain selection model is shown in a flowchart in Fig. 2 (left). According to a parcel's size, we assumed for XL parcels that delivery with a cargo bike is not suitable as these parcels already consume a high proportion of the available capacity, drastically limiting the number of stops per cargo bike tour and, hence, making those tours inefficient. Consequently, all XL parcels can only be delivered by light-duty vehicles. For all other parcel sizes, this option is also always available. However, parcels of size S, M, and L, according to the classification in Section 3.2, can also be foreseen for other transport chain options. For those, distance measures are analyzed to further exclude inappropriate transport chains. If the customer is closer to the distribution center than the maximum range of a cargo bike, transport chain B (solely cargo bike) is considered in the choice set. Furthermore, the distance between the customer and its closest city hub is checked. If this exceeds the maximum range of a cargo bike, no further transport chain options are added to the choice set. However, if this distance is the same or less, transport chain C, comprising a light-duty vehicle and cargo bike, is added to the choice set. In that case, the transport chains incorporating the cargo tram are also reasonable. Nevertheless, a further check of the distance between the distribution center of a CEPSP and the next tram stop, where parcels can be handed over to the cargo tram, has to be done. If this is above a maximum threshold, transport chain E, with an additional leg to transport the parcel with a light-duty vehicle to the next tram station, is added to the choice set. If not, transport chain D incorporating the cargo tram but without the additional leg is added to the choice set. This decision tree is repeated for each parcel, and hereby, transport chain choice sets are generated for each parcel. The respective maximum values can be adapted by the researcher and are subject to scenario simulations in the further course of that study.

4.2.2. *Utility-based transport chain selection*

The subsequent *utility-based decision model* determines the actual transport chain to be used for each parcel based on the available choice set. As described in the literature section, the application of a multi-level vehicle routing problem would be one possible solution to determine the


Rule-based selection model

Utility-based selection model

Fig. 2. Flowcharts of rule-based (left) and utility-based (right) decision models.

transportation chain and its consequent trip pattern for each CEPSP individually. Hereby, the target of a cost-minimizing approach for each CEPSP could be achieved. However, the requirement is the development of a global decision-making process throughout all different CEPSPs. Since different cost structures and processes are expected at the individual CEPSPs, one VRP would have to standardize all those aspects in distinct variables, which is unlikely to accurately reflect the decision-making behavior of all CEPSPs. As an appropriate alternative, a discrete choice approach was chosen, which can reflect the decision between the limited and discrete number of transport chain alternatives as well as a global decision behavior over all CEPSPs. Their flexible structure allows the consideration of a variable number as well as various kinds of influencing factors and hence, also the required basic established decision variables in logistics. Furthermore, literature proposes discrete choice models to reflect logistical decisions better than other statistical and aggregated models, especially in an urban context (see Boerkamps et al. (2000)).

According to the recommendations by de Jong and Ben-Akiva (2007), a multinomial logit (MNL) is applied for the *utility-based decision model*. Hereby, the possibility of flexible model adoptions is supported, for example, if further transport chain options with different transport modes need to be investigated in a further application. Within that model stage for each parcel, the utility is calculated for all transport chains available in the choice set. Due to the novelty of the cargo tram, only basic logistical decision variables are considered in the utility function for each transport chain, namely transportation costs, distance, and time. Consequently, the utility function for transport chain m is given as

$$V_m = \beta_{m,0} + \sum_{i \in m} \beta_{i,costs}{}^{*} x_{i,costs} + \sum_{i \in m} \beta_{i,distance}{}^{*} x_{i,distance} + \sum_{i \in m} \beta_{i,time}{}^{*} x_{i,time} \tag{1}$$

with the alternative specific constant (asc) $\beta_{m,0}$, the utility coefficients $\beta_{i,(costs,distance,time)}$ and the corresponding utility contributions $x_{i,(costs,distance,time)}$ of each mode i in transport chain m. Transport costs consider the mode-specific costs of each mode used in a transport chain as well as fixed labor costs for a possible handover process. Parallel, transport time covers the time for transportation as well as a fixed time amount for handling processes at possible handover points. Furthermore, the distinct utility contributions of all modes within a transport chain are normalized with the corresponding capacity of each mode as the decision is made on the base of single parcels. The methodology is not limited to those factors and can be flexibly extended in future applications if the corresponding data is available. However, to investigate the proof-of-concept, those three main logistical decision variables are considered in the study at hand.

Fig. 2 (right) shows the realization of the *utility-based* stage of the transport chain selection model in a flowchart. The starting point is the choice set of transport chains generated in the *rule-based decision model*. If the choice set contains only one transport chain, the parcel needs to be delivered in a single-leg transport chain using a light-duty vehicle. Hence, no further adaptions are necessary as this corresponds with the status quo in *logiTopp*. In all other cases for each transport chain in a parcel's choice set, the previously described utility function is applied, and the choice probability for each transport chain m in a parcel's j choice set M is generated based on the commonly known function by Ben-Akiva and Lerman (1985).

$$P_m(j) = \frac{e^{V_{j,m}}}{\sum_{m \in M} e^{V_{j,m}}}. \tag{2}$$

Based on these probabilities, the actual transport chain decision is performed using a weighted random draw procedure, determining a unique transport chain for each parcel. However, in case a multi-leg transport chain is chosen, further adoptions in the existing *logiTopp* framework have to be done, which is described in the next subsection.

4.2.3. *Integration of two-stage transport chain selection model in logiTopp*

Fig. 3 shows the integration of the developed two-stage transport chain selection model in the modeling framework *logiTopp*. The new modeling step is integrated as an intermediate decision process between the long- and short-term module. Hence, all information generated in the long-term module can be used in the transport chain selection model. Consequently, after the number of parcels per customer, their

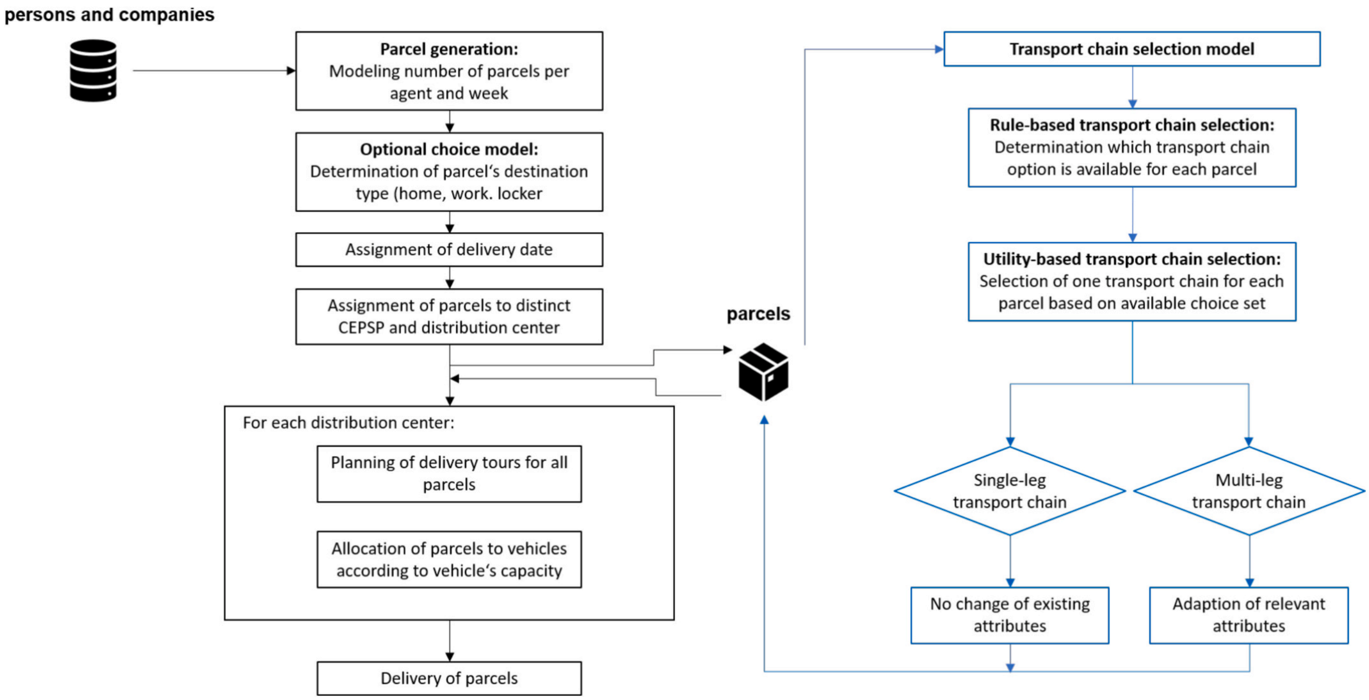


Fig. 3. Integration of two-stage transport chain decision model (blue) in existing logiTopp framework (black). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

delivery date, and the responsible CEPSP are determined for each parcel, the transport chain selection model is applied according to the previously described two-stage procedure. If a single-leg transport chain is chosen, no further adaptions must be done. In case a multi-leg transport chain is chosen, such as those involving the cargo tram, relevant attributes must be adapted. This mainly concerns the information of the involved city hub and, in case one leg is done by the cargo tram, an adaption of the arrival time according to the public transit timetable. After that, the tour planning can be performed for each CEPSP at each distribution center as initially implemented in *logiTopp*, but considering the modeled transport chain option for each parcel.

5. Application of the model

We applied our modeling framework to the city of Karlsruhe, which is highly suitable for the evaluation of rail-based city logistics due to its well-developed rail network in the city, in the suburbs - where distribution centers are located - and in between. Within that study area, the modeling framework *logiTopp* already models and simulates the parcel demand of about 305,000 parcels of private and establishment receivers over one week. Moreover, as outlined in the literature section, Karlsruhe is currently piloting a cargo tram system relying on combined freight, i. e., parcel and passenger transport within the same tram vehicles (AVG, 2021). The project relies on cargo bikes for the shipment on the very first and last mile. Their trailers shall be pre-packed at the CEPSP's distribution centers. To achieve a smooth integration into the passenger operation, technical developments for fast, automated loading and unloading of cargo bike trailers to and from the tram are planned to comply with the specified tram stop times in the initial timetable. However, to implement the two-stage transport chain selection model developed in this study, further information from the Karlsruhe pilot had to be integrated into the modeling framework to test the proof-of-concept of the methodology and to analyze the transport-related effects of urban rail-based freight transport.

First, Karlsruhe's current urban tram network must be considered explicitly since, according to the public transit operator, the cargo tram must be seamlessly integrated into the public transit system (AVG, 2021). This also results in constraints and legal barriers that must be considered when combining public and freight transport. Consequently, we transferred the already existing public transit timetable for passenger transport to the cargo tram, which builds the base for transportation times. As the delivery with light-duty vehicles is currently modeled to start at 8 a.m. due to operational reasons of the corresponding workforce, we also adopted that assumption to the cargo tram.

Because the cargo tram goes along with the installation of intermodal city hubs, which are currently not yet determined by urban planners, we next had to identify relevant city hub locations within the study area. For the identification of tram stops as possible city hubs, overground tram stops are essential as they enable effortless connectivity to cargo bikes. Furthermore, these stops must be served by tram lines passing the original handover stop while providing enough space to store transport vessels (Bogdanski & Cailliau, 2022). Besides that, as many households as possible should be reached from a city hub. To maximize economies of scale, only the smallest possible number of stops should be expanded to serve as city hubs. In total, we identified two city hubs providing rail connectivity to all distribution centers for the study area while located within the zone with the highest parcel demand concentration and sufficient space for handover processes and temporary storage of cargo bike trailers. These two locations were integrated into the modeling framework. Moreover, depending on the already existing locations of the freight operators' distribution centers and the corresponding tram line running in its vicinity, the nearest tram stops for handover are also assigned.

Furthermore, the implementation requires network-specific cost-, distance-, and time-related parameters for the freight transport between the distribution centers and city hubs, as well as between city hubs and receivers, to apply the utility-based decision model for transport chains. Costs were adapted according to the already implemented mode-specific cost matrix on OD basis in *mobiTopp*. For example, truck costs are based on the car cost matrix multiplied by a factor of 1.42 calculated based on higher fuel and vehicle costs for light-duty vehicles compared to regular cars (HBEFA, 2024). Moreover, tram costs are set to 0 as only existing passenger tram rides are considered, and additional costs can be subsidized by public funds, at least in the early stage of the project's implementation. Furthermore, labor costs are introduced for all human resource-demanding activities (driving light-duty vehicles and cargo bikes, handover processes) within a transport chain. Labor costs are calculated based on the transportation time and fixed time values for possible handover processes multiplied by an average employee's cost of 29 € per hour in Germany (DESTATIS, 2024). For transportation times, the same logic was applied. Hereby, cargo tram times are aligned with the timetable of public transit, and hence, transportation times listed in *mobiTopp's* already implemented OD time matrices for public transit are used for cargo trams. For cargo bikes, the times for bikes were considered. Moreover, distance values were transferred from the already implemented OD distance matrix. The utility-based decision model also requires a definition of the β parameters. Due to the novelty of the cargo tram and the lack of necessary data, we set all parameters to the level of 1, as an arbitrary determination of the parameters would not bring any gain in knowledge. However, as transportation time and costs are typically considered negative, we set those β parameters to -1. Finally, mode-specific parcel transportation capacities were implemented in the modeling framework based on literature research (BIEK, 2017; Gruber, 2021) aligned with the pilot's requirements and status quo in Karlsruhe.

Due to the previously described assumptions, especially regarding the realization of the utility function, we decided to do a scenario analysis to focus on the effects of the variation of single variables and aim to evaluate the proof-of-concept of the new methodology rather than focusing on the precise forecast of the transport-related effects of a cargo tram. Given that focus, the scenarios should reflect the variation of parameters that are used within the proposed two-stage transport chain selection model and are not determined by external circumstances such as distances between distribution centers and recipients. Regarding the rule-based stage, this only concerns the cargo bike range. Based on Gruber and Narayanan (2019), cargo bikes typically can be operated efficiently within a range of 3 km, sometimes even up to 5 km, compared to motorized transport. Accordingly, we use those limits as cargo bike ranges in our scenarios. Regarding the utility-based stage, we limit our scenario analysis to variations of the base utility as an aggregated measure to capture utility differences. Since we focus on relative comparisons due to the lack of validation and calibration data sources, we have arbitrarily chosen + 1 as one base utility and + 3 as a significantly higher base utility relative to the values that the other variables of the utility function can assume. To cover all possible combinations, the analysis of the proof-of-concept should cover scenarios where the cargo tram and light-duty vehicles have the same base utility and where the base utility of one or the other alternative is higher. Hence, we calculated a total of six scenarios. A status quo scenario without a tram as a freight transport mode, namely with light-duty vehicles, is simulated as a comparison scenario. In the following, Table 2 gives an overview of the definition of varied parameters within each scenario.

Table 2
Overview of parameter variation for each scenario.

Scenario No.	Scenario Name	Cargo bike range	Asc cargo tram	Asc LDV
0	Base scenario	–	–	–
1	3km_equal_utility	3 km	$\beta_{Tram,0} = 1$	$\beta_{LDV,0} = 1$
2	5km_equal_utility	5 km	$\beta_{Tram,0} = 1$	$\beta_{LDV,0} = 1$
3	3km_higher_utility_tram	3 km	$\beta_{Tram,0} = 3$	$\beta_{LDV,0} = 1$
4	5km_higher_utility_tram	5 km	$\beta_{Tram,0} = 3$	$\beta_{LDV,0} = 1$
5	3km_higher_utility_LDV	3 km	$\beta_{Tram,0} = 1$	$\beta_{LDV,0} = 3$
6	3km_higher_utility_LDV	5 km	$\beta_{Tram,0} = 1$	$\beta_{LDV,0} = 3$

6. Results

Given all the generated parcels with their corresponding attributes in *logiTopp* that need to be shipped to private and establishment receivers during one week, the two-stage transport chain selection model is applied to each parcel and scenario.

In the first stage, the rule-based decision procedure as described in Section 4.2.1 is computed within the agent-based simulation framework to check the availability of transport chains for each parcel and each scenario. This stage is independent of any variation in the alternative specific constants of the cargo tram and light-duty vehicle. In addition, the location of city hubs and distribution centers is fixed over all scenarios. Hence, differences occur only regarding the variation in the cargo bike ranges. Consequently, the calculated choice sets of transport chains are the same for scenarios 1, 3, and 5 (3 km cargo bike range) as well as for 2, 4, and 6 (5 km cargo bike range). In the base scenario, only light-duty vehicles transport parcels, which is why no rule-based decision is applied.

Even with a cargo bike range of 3 km, about one-third of all parcels already have a transport chain containing the cargo tram in their choice set. The receivers of parcels seem to be sufficiently close to the installed city hubs, as already a large proportion is eligible to be delivered by a cargo tram transport chain. However, extending the range to 5 km shows a reasonable increase of that share to more than half of all parcels. The extension of the cargo bike range also affects the possibility of shipping via the transport chain only containing the cargo bike. In the case of 3 km, less than 10 % of all parcels could be shipped only by cargo bikes, whereas this proportion increases to about 20 % in the case of the 5 km cargo bike range. This is reasonable as the CEPSPs' distribution centers are mostly in the suburban area, whereas the receivers are primarily modeled within the city area of Karlsruhe. Hence, the distribution centers are often too far from their receivers, making the only cargo bike shipment less suitable if the range of the bikes is not sufficiently high. The geographical locations of distribution centers and city hubs are illustrated in Fig. 4.

The actual transport chain selection takes place in the utility-based stage of the overall selection model. Hereby, the multinomial logit model and the procedure as described in Section 4.2.2 were applied to each parcel's transport chain choice set in each scenario. As the main focus of our study was the analysis of a supplementary urban rail-based shipment of parcels on the current exclusive light-duty vehicle shipment, we focus on the direct comparisons between light-duty vehicle shipment and transport chains containing the cargo tram in the following. Table 3 presents this comparison over all scenarios.

The results show that a non-negligible proportion of about 15 % of transport chains with a cargo tram is chosen in case of equal alternative specific constants (base utility) for cargo trams and light-duty vehicles. However, under the same conditions but with a greater cargo bike range, the proportion could be further increased to about 19 %. Even though these results indicate that the developed methodology leads to overall reasonable results, their absolute magnitude strongly depends on the assumptions stated in the previous section. For example, an increase in the prices for shipping via cargo trams would already reduce this effect. Table 3 further shows that with an increasing cargo bike range, transport chains with cargo trams are chosen more often. This can be referred to the effect that, in this case, cargo tram transport chains are also more often in the parcels' choice set. As expected, the highest reduction (~ 40 %) of light-duty vehicle usage for parcel shipments is observable in scenario 4, where the operating distance for cargo bikes is assumed to be the highest, and the base utility for the cargo tram is greater than its equivalent of the light-duty vehicle. Consequently, the opposite effect, with only less than 5 % proportion of cargo tram shipments, is observable in scenarios 5 and 6, where the base utility for cargo tram is lower than that for light-duty vehicles.

As an additional analysis, Fig. 4 shows the geographical distribution of the simulated results exemplary for scenario 1. It becomes clear that

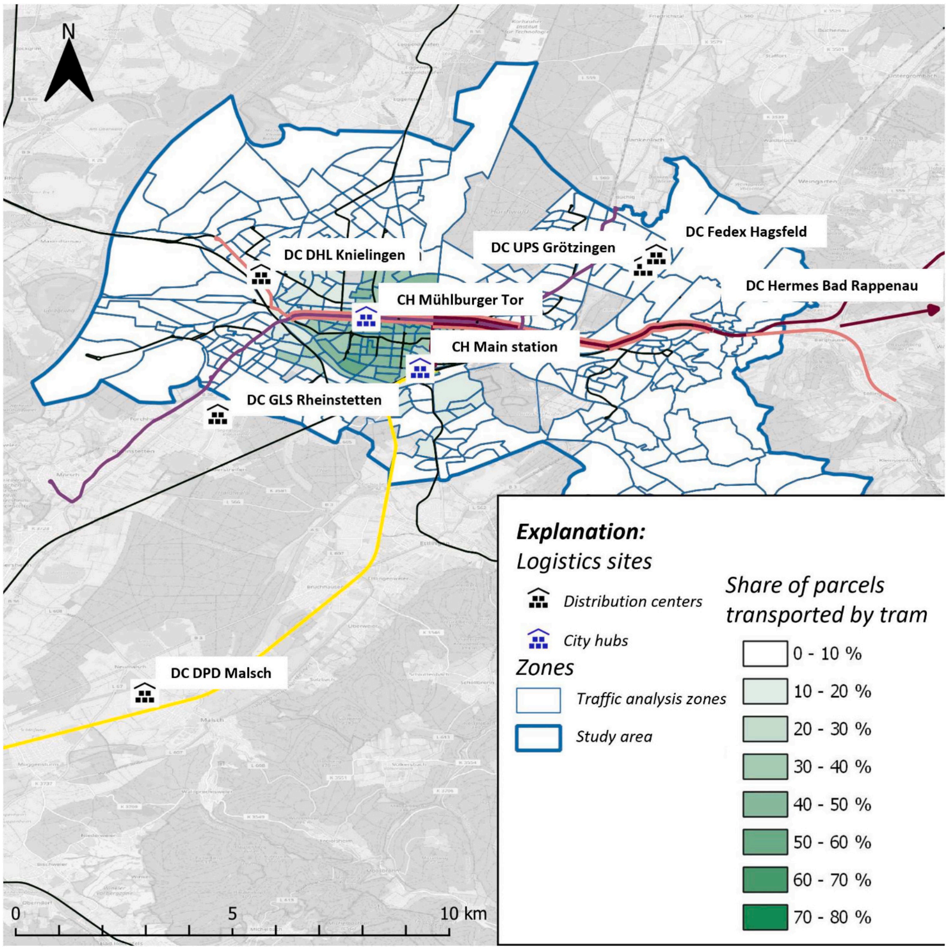


Fig. 4. Spatial comparison of logistics sites and parcel transport by cargo tram for scenario 1.

Table 3
Simulation results for parcel transport by light-duty vehicles and cargo tram for each scenario.

Scenario Number	Scenario Name	Light-duty vehicles	Cargo tram
0	Base scenario	305,254 (100 %)	–
1	3km_equal_utility	260,579 (85.4 %)	44,675 (14.6 %)
2	5km_equal_utility	246,980 (80.9 %)	58,274 (19.1 %)
3	3km_higher_utility_tram	219,745 (72.0 %)	85,509 (28.0 %)
4	5km_higher_utility_tram	189,998 (62.2 %)	115,256 (37.8 %)
5	3km_higher_utility_LDV	295,346 (96.8 %)	9,908 (3.2 %)
6	3km_higher_utility_LDV	292,516 (95.8 %)	12,738 (4.2 %)

with increasing proximity to a city hub, the share of parcels transported by cargo tram increases as well, which again is a reasonable result obtained from the transport chain selection model. However, in the presented scenario, the proportion of traffic analysis zones where no cargo tram shipment is available is much greater than where it is available. Hence, the analysis also makes clear that there is still a high potential to further increase the share of cargo tram shipments. In line with the overall scenario results presented in Table 3, we assume that over all scenarios, there is still a significant volume of light-duty vehicle shipments that could be further reduced, for example, by introducing additional city hubs, which would make a cargo tram based shipment more suitable for more parcels. However, as mentioned before, the magnitude of that effect strongly depends on the valuation of the cargo tram in a real-world operation and is currently subject to assumptions in the model.

The overall effects of a rail-based parcel shipment on the transportation system are of particular interest. Hence, Fig. 5 shows the effects of the transport chain selection within the travel demand model for parcel deliveries across all scenarios. The trips of the cargo tram are not taken into account since, in our study, we assumed that cargo and passengers are transported combined within the same vehicle; hence, no additional trips are induced. Further, it should be mentioned that only the deliveries to private receivers are considered in the subsequent analysis as these are more suitable for a cargo tram shipment due to less restrictive delivery times, etc. Therefore, the following analyses refer to a subset of the previously described ‘parcel population’. However, parcels shipped to private consumers account for approximately 154,000 parcels, about half the total parcel volume.

Concerning the induced trips per transport mode, the base scenario without cargo tram indicates approximately 70,000 trips, whereby more than one delivery can be made on one trip or at one stop. Analogous to the previously presented results, the share of cargo tram parcels increases from scenarios 1 to 4. This effect can also be observed clearly in the sharp drop in the number of trips made by light-duty vehicles. In scenario 4, the most optimistic scenario for cargo tram usage, only about 38,000 trips are made by light-duty vehicles. At the same time, the number of cargo bike trips increases only slightly. This suggests that the efficiency in terms of the utilized capacity of cargo bikes and trams is considerably high. In scenarios 3 and 4, significantly more parcels can be

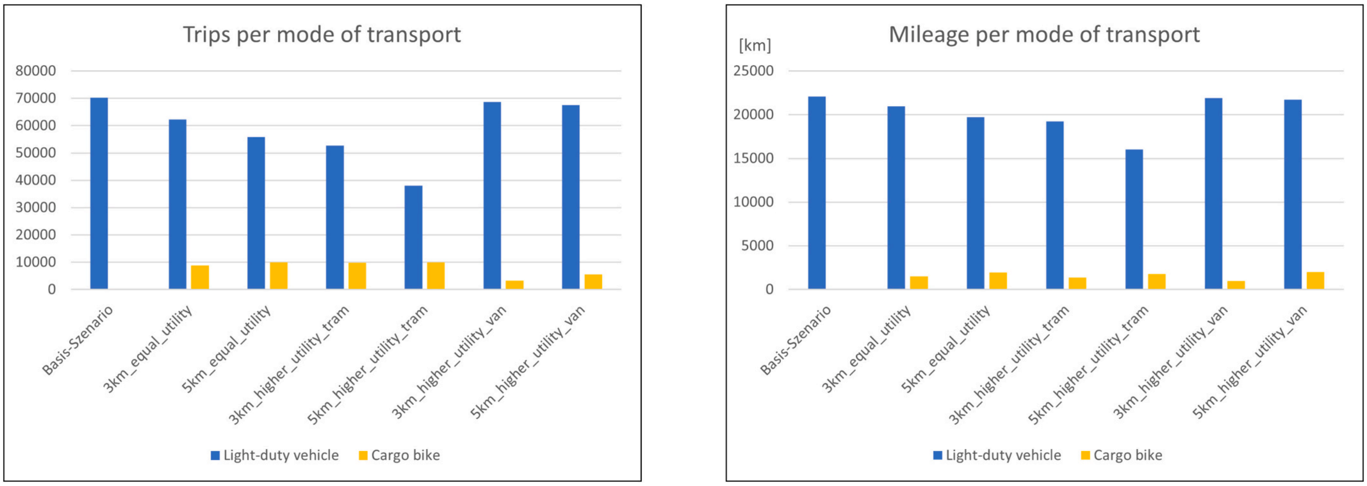


Fig. 5. Simulation results of overall mileage and number of trips.

transported to the same addresses or households without requiring significantly more trips. In the scenarios with greater base utility for light-duty vehicles, almost all parcels are delivered by the same number of vehicles, and the number of trips is almost as high as in the base scenario. Although significantly fewer parcels are delivered by cargo bike (only 25 % compared to scenario 1), the number of cargo bike trips only decreases by half to two-thirds.

The tendencies are similar for the induced mileages per transport mode. However, it is even more noticeable that in scenarios 5 and 6, the total mileage of light-duty vehicles is 1–2 % lower than in the baseline scenario. In an exclusively cost-optimized selection model, such a result would not be comprehensible since the overall costs, e.g., due to the labor time, are consistently higher in these scenarios than in the base scenario. Under this assumption, it would not be comprehensible that the transport chains involving cargo trams are selected. Since, based on the discrete choice approach and the associated logit model, the benefits of the transport chains consist of more than just the costs, such supposedly uneconomic decisions can also occur. Other utility contributions, such as transportation time and distance, were weighted equally for both transportation chains in this paper due to the lack of data. Therefore, the decisions are only attributable to different values in the OD matrices for the respective modes of transport.

Generally, the analysis shows the model's ability to precisely evaluate the transport-related effects of the cargo tram based on the newly developed transport chain selection methodology and its integration into *logiTopp*. Again, in the current version of the method, the absolute values cannot be granted as fully reliable based on many practical uncertainties with supplementary cargo tram city logistics. Rather, however, they already serve to provide the proof-of-concept for the method and its integration into an urban freight demand model with comprehensible results and trends. Relevant assumptions affecting the absolute magnitude of the results do not only concern the assumptions made in the model application but also the assumptions and developments of the overarching pilot project in Karlsruhe, which served as an example for the model application presented in this study, e.g., sufficient available transport capacities for parcels in passenger trams, the technical realization of automated loading and unloading processes, etc.

7. Conclusion

To provide a sustainable response to the rising volume of parcels, which on the one hand, reduces emissions but also contributes to an overall easing of transport-induced externalities, urban and transport planners are working on solutions for new concepts for city logistics. In this paper, we could contribute to the analysis of a so far less researched solution, namely the delivery using the existing urban rail infrastructure in combination with cargo bikes with handovers at intermodal city hubs. Due to the more complex mode choice, we developed a two-stage decision model based on transport chains. We integrated this into the existing agent-based travel demand model *mobiTopp* and its logistical extension *logiTopp*. The model comprises a rule-based stage, which first queries the logical availability of a specific transport chain, and a utility-based stage, which determines the actual transportation chain based on a multinomial logit decision.

At the example of the city of Karlsruhe, Germany, and their pilot project of a combined passenger and freight tram within the same vehicle, we could show that the developed methodology simulates overall reasonable results and reveals plausible effects. In different scenarios, we could show that the integration of an urban rail-based parcel transportation system using cargo trams can have the potential to contribute to a reduction in trips and mileage of light-duty vehicles when the cargo tram is integrated with passenger trams. However, we could also show that the maximum range for cargo bikes greatly influences the actual transportation chain selection as this parameter significantly impacts the logical rule-based decision, which transport chain can be considered for which parcel. With greater ranges, the potential for cargo tram shipments increases as well. This is directly connected to the location and number of corresponding city hubs. With more city hubs, the range of cargo bikes is of minor importance, but the potential for cargo tram shipment still increases. However, urban and transport planners, and also CEPSPs, have to weigh the additional costs for city hubs against their potential on the transportation system. Additionally, we could also show that the base utility plays a major role in the direct comparison between cargo tram and light-duty vehicle decisions. As the decision is taken by the CEPSPs, mainly interested in reducing their costs and satisfying their customers, transport planners and politicians should consider an appropriate incentive system or legal regulations to promote rail-based shipment.

However, the presented modeling approach still had to work with a few workarounds as the cargo tram is not yet an established mode, and hence, its potential usage characteristics are unclear, leading to multiple assumptions for the model application and, hence, a limited significance of the values shown. Although we support the assumption that the operating costs of the CEPSP should dominate the utility-based modeling stage since the companies' decisions are more rational than the individual mode choice in passenger transport, further analysis of the factors influencing that decision has to be undertaken in future work. In addition, empirical behavioral support for the identified factors and their influence on the CEPSPs' transport chain selection has to be focused in future work. Due to the small number of existing CEPSPs, standard solutions in transport research, like a stated choice survey among CEPSPs, do not seem to be suitable. For that reason, we currently apply an alternative method called 'analytical hierarchy process' that can capture empirical insights even if the sample is small. In this context, we conduct interviews with CEPSPs to obtain an evaluation of the different mode choice decision criteria. These results are then translated into utility theory and transformed into utility-based decision models. The work is still ongoing. Moreover, in the application presented in this study, we adapted the existing OD matrices from the passenger travel demand model *mobiTopp*. In the future, more well-founded, precise OD matrices for all specific vehicle types should be considered.

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CRediT authorship contribution statement

Lukas Barthelmes: Writing – review & editing, Writing – original draft, Validation, Project administration, Methodology, Investigation, Data curation, Conceptualization. **Mehmet Emre Görgülü:** Writing – review & editing, Writing – original draft, Validation, Data curation, Conceptualization. **Jelle Kübler:** Validation, Software, Methodology, Data curation. **Aljoscha Löffler:** Validation, Software, Methodology, Investigation. **Martin Kagerbauer:** Supervision, Project administration, Conceptualization. **Peter Vortisch:** Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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