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Urban consolidation and cargo bikes: a simulation study

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Abstract

In the course of congested city centers, increasing delivery volumes and a growing environmental awareness, both local public administrations and logistics service providers are faced with the challenge of finding sustainable solutions for urban freight transport. Two promising approaches for urban logistics are consolidation concepts and cargo bicycles. In our paper, we present hybrid agent-based and discrete event simulation model to analyze the integration of cargo bikes into urban consolidation concepts across multiple logistics service providers. Based on a case study of the city of Frankfurt we compare different urban logistics schemes. The simulation results show that cargo bikes can be a suitable addition to urban consolidation concepts from both an environmental and financial point of view.

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Keywords: Cargo bikes, Urban Consolidation Centers, City Logistics, Simulation

1. Introduction

Today, more than 50% of the world's population lives in cities In Europe, this share even exceeds 75% and further increases are to be expected globally (United Nations (2015)). Along with the growing number of people living in urban areas, the demand for goods deliveries and thus freight transports in urban areas is increasing as well. While urban freight transportation takes a major role in the economic system of cities, it has also severe negative effects on the quality of life in urban areas in form of congestion as wells as pollutant and noise emissions. As a result of these negative effects and in light of international and national regulations on air quality control, public administrators, as well as logistics service providers (LSP), are being challenged to not only find efficient and effective but also sustainable solutions for the transportation of goods in urban areas. Numerous urban logistics

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projects have been initiated since the 1990s to address this dichotomy between economic efficiency and environmental compatibility. Although different implementation concepts have been pursued, most concepts have in common the fundamental idea of bundling urban freight traffic in order to relieve the urban infrastructure and improve the economic efficiency of urban freight traffic. Within the scope of consolidation, the concept of Urban Consolidation Centers (UCC) which describe facilities in the proximity of an urban area to bundle urban freight transports to be transshipped onto vehicles with increased load factors (Allen et al. 2012), has received much attention in research and practice. However, asides from the consolidation perspective, innovative vehicle conceptions ranging from delivery drones to autonomous robots have been introduced into urban logistics as an alternative to conventional vehicles in recent years and led to a plurality of possible concepts. Among these technological innovations in urban logistics, electric cargo bikes receive increased attention due to lower emissions and lower traffic impacts and therefore are tested in pilot studies in many places (see e.g. Verlinde et al. (2014), Nocerino et al. (2016)). In connection with the growing interest in cargo bikes, new forms of consolidation and transshipment, such as micro-consolidation as well as mobile- and micro-depot-based concepts, have been introduced in order to make the integration of cargo bikes into urban freight systems possible. These concepts generally describe transshipment points from which last-mile deliveries are completed by cargo bikes. In contrast to classical depots and UCCs, they are located within a city center to shorten the delivery distances. We use the term micro-depot (MD) to describe transshipment points used by only one carrier and use the term micro-consolidation-centers (MCC) for transshipment points collaboratively used by multiple carriers.

Even though several cargo-bike-based schemes have been tested in pilot studies, there is very little guidance to support the decision-making of LSP regarding the integration of cargo bikes and comparison of different possible options. Moreover, many, if not most of the pilot studies are initiated by a single LSP and thus the aspect of consolidation is largely neglected despite being one of the core aspects of urban logistics. Addressing these two research gaps, we show in this paper how the integration of cargo bikes into different consolidation schemes across several LSP can be analyzed with the help of a hybrid agent-based and discrete event simulation approach and provide pointers for a decision support tool for LSPs. Thereby we assess the financial and operational aspects from the view of logistics service providers as well as the resulting traffic effects of these schemes from an urban decision maker's perspective.

The outline of this paper is as follows: In Section 2 we briefly discuss the related literature on cargo bikes in urban logistics systems and related consolidation schemes. In Section 3 we present our simulation approach to assess different consolidation concepts. Section 4 describes an exemplary case study using the city of Frankfurt. The results of the case study are discussed in Section 5. Finally, Section 6 concludes and provides pointers for future research.

2. Related literature

The commercial applications of cargo bikes can be distinguished into postal services, courier services, parcel services, home delivery services, internal and on-site transport, and service trips (Rudolph and Gruber 2017). Several studies and surveys have been conducted to broaden the understanding of the commercial application of cargo bikes. For example, studies performed by Gruber et al. (2014), Maes and Vanelslander (2012), and Schliwa et al. (2015) aimed to gain insight into the cycle logistics market with special focus on bike couriers. By conducting interviews with courier services and experts it was shown that the cycle logistics markets is dominated by relatively small business with limited operations and comprises a variety of different cargo bike types. The studies indicate that there exists a specific market for cycle logistics, as for example Gruber et al. (2014) estimate that up to 42% of courier services performed by cars could be substituted by electric cargo bikes in order to help to reduce externalities. A further survey of cargo bike operators in Paris by Koning and Conway (2016) confirms that the usage of cargo bikes in urban freight aided to reduce externalities and has rapidly increased between 2001 and 2014. However, Schliwa et al. (2015) note that the viability of using cargo bikes is largely impacted by geographic factors, such as a high population density and narrow streets in historic centers as well as the presence of urban access regulations for motorized vehicles. Similarly to Maes and Vanelslander (2012), the authors suggest that additional incentives from local authorities are required to further facilitate the use of cycle logistics. In a more recent study, Rudolph and Gruber (2017) distinguish between environment-specific, company-specific, and product-specific drivers and constraints for the use of cargo bikes and provide further recommendations for wider adoptions of cargo bikes in commercial applications.

Focusing on the integration of cargo bikes into urban freight systems, Hofmann et al. (2017) provide a classification of six cargo bike schemes (see Fig. 1). Therein they differentiate between direct point-to-point services, single-level and two-level urban distribution schemes using micro-depots (MD) and micro-consolidation centers (MCC) in addition to classical UCCs. The proposed schemes not only differ regarding the number of levels but also in whether shipments from different origins (e.g. from several LSPs) are consolidated in UCCs or MCCs or just transferred onto cargo bikes in MDs.

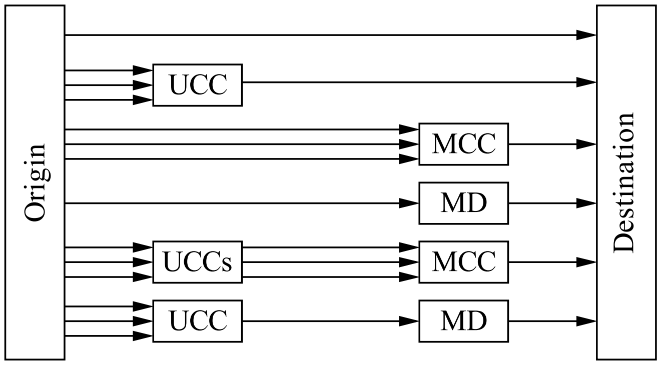

Fig. 1. Classification of cargo-bike-based schemes in urban freight transport (adapted from Hofmann et al. 2017).

In addition to fundamental considerations on the possible demand for cargo bikes in urban logistics and its facilitation, a number of pilot studies focusing on parcel deliveries were carried out and reported in the literature. Early tests in combination with micro-consolidation centers in Paris (Dablanc 2011) and London (Leonardi et al. 2012) have demonstrated that cargo bikes can be a viable option for urban freight systems. More recently, Nocerino et al. (2016) report the results from four Italian pilot studies, where the potentials of various electric cargo bicycles and electric scooters for urban freight transport were examined for smaller and larger LSPs. The pilot results indicated energy cost savings for all four cases and proved to be a feasible alternative to conventional vans.

Apart from stationary MDs, also mobile MDs have been tested in pilot studies. Verlinde et al. (2014) describe a three-month pilot trial of a mobile MD in Brussel. In line with other trials, they report a significant decrease of diesel kilometers compared to the operations before the trial, which however doubles the costs of the LSP. A similar pilot has been run by UPS in Hamburg, where swap bodies function as mobile MDs (Bogdanski 2017). Since logistics spaces are scarce in urban areas, several authors, such as Rudolph and Gruber (2017) and Bogdanski (2017) propose the shared use of MCCs, where more than one LSP use an urban depot as the base for cargo bike operations. Analogously to this approach, Navarro et al. (2016) portray the results of two pilots using electric cargo tricycles and transshipment points in Barcelona and Valencia. In opposition to many other pilots, a micro-consolidation center is tested where LSPs cooperate together to share the same vehicles for the last-mile delivery. To evaluate the initiative in both cities, they provide a detailed assessment of costs and externalities. Similarly, in Berlin, a pilot trial named KoMoDo has been started recently, where five LSP share an MCC together, but opposed to the trials in Spain still remain to perform deliveries by cargo bikes separately on their own (BIEK 2018).

Besides reports from pilot trials, several analytic approaches on cargo bikes in urban logistics have been presented in the literature. Arvidsson and Pazirandeh (2017) conduct an ex-ante evaluation of an urban freight system which utilizes public transports (e.g. bus, truck, barge, or tram) circling a city and thus functioning as mobile depots for cargo bikes or light electric vehicles. In a case study, they investigate the usage of a freight bus serving as a mobile-depot for cargo bikes versus conventional deliveries performed by vans. Assuming varying utilization rates of the bus, the authors show that the proposed concept can be financially viable while providing environmental and social benefits. Meanwhile, Anderluh et al. (2017) present a heuristic for a two-echelon city distribution scheme with temporal and spatial synchronization between cargo bikes and vans. They demonstrate that the combined usage of cargo bikes and vans can be a financially viable option.

A frequently used research method for the investigation of cargo-bike-based urban freight systems are simulations (see table 1). Melo and Baptista (2017) investigate the effects of cargo bikes in urban logistics from the point of view of public administrators as well as transport operators. In their microscopic traffic simulation, they consider a limited area with maximum linear distances of two kilometers to assess environmental and social impacts as well as the cost and service level of deliveries using cargo bikes versus deliveries using conventional vans. The simulation results show that cargo bikes can lead to large environmental benefits and replace up to 10% of conventional vans without affecting the operation and traffic performance of the urban system. More recently, Marujo et al. (2018) study a mobile-depot-based concept, where conventional trucks function as transshipment points for the urban distribution of beverages in Rio de Janeiro by motorized cargo tricycles. Thereby they assess operational, financial, and environmental effects of the studied concept with a field study and Monte Carlo Simulation. Their results indicate that negative environmental effects can be reduced significantly while maintaining a similar operational performance. However, from a financial perspective, only areas with low average delivery drop size seem to profit financially from the mobile-depot-based concept.

Hofmann et al. (2017) propose a discrete-event simulation (DES) approach to assess the integration of cargo bikes into urban B2B-distribution systems. Based on a case study of the French city of Grenoble the authors compare the overall vehicles kilometers and delivery times of direct UCC operations with vans versus a two-stage system, where loads are transferred onto electric cargo bikes at 4 or 3 MDs within the city. The results show reduced overall vehicles kilometers for the two-stage system due to the UCC using larger trucks to supply the micro-depots and thus fewer routes from the UCC to the city center. Fikar et al. (2017) present an agent-based simulation (ABM) for urban last-mile deliveries including cargo bikes and MDs. With their model, they investigate food deliveries in an area with restricted access, where orders need to be picked up by an LSP at restaurants and delivered to customers within a guaranteed duration. Thereby, the LSP utilizes a varying number of cargo bikes which are operated by freelancers as well as conventional vehicles and MDs for transshipment between cargo bikes and conventional vehicles. The results point out the potential of MDs to reduce delivery delays and underline the importance of having enough freelance cargo bikes available. Lastly, Arnold et al. (2018) investigate the use of cargo bikes for B2C urban distribution by means of simulation as well. Using the city of Antwerp as a case study, they compare the current urban B2C parcel distribution to alternative scenarios including customer self-pick-ups and cargo bikes. In line with previous studies, the authors show that the integration of cargo bikes can lead to drastic reductions in externalities. However, from a cost perspective, their findings suggest that a sufficient density of MDs, as well as the possibility for self-pick-ups, is required to make the cargo-bike-based delivery system also financially viable.

The overview of the related works shows that although urban freight transport is a widely-studied research area, the integration of cargo bikes into urban freight systems is a relatively new research stream. A number of different concepts and applications have been studied by means simulations. However, the existing studies primarily focus only on the operations of a single LSP and do not consider possible consolidation among several LSP.

Table 1. Overview of simulation studies on cargo bikes in urban freight transport.

Authors	Simulation method	Country	Application	Considered costs		Type of MD	Notes
				Internal	External		
Arnold et al. (2018)	DES	Antwerp, Belgium	Parcel (B2C)	●	●	Fixed	Includes customer self-pick-up from the depots
Fikar et al. (2017)	DES, ABM	Vienna, Austria	Food (B2C)			Fixed	
Hofman et al. (2017)	DES	Grenoble, France	Parcel (B2B)			Fixed	
Marujo et al. (2018)	Monte Carlo	Rio de Janeiro, Brazil	Beverages (B2B)	●	●	Mobile	Includes deliveries by hand cart
Melo and Baptista (2017)	Microscopic traffic simulation	Porto, Portugal	Parcel (B2B)	●	●	–	Max. 2 km distance in viewed area thus no MD and vehicle routing

3. Simulation methodology

As presented in our review of related literature, simulation is a common method to analyze cargo-bike-based logistics systems. But also in other contexts of urban logistics, simulations have proven to be a well-established methodology for analyzing urban freight systems (see e.g. Jlassi et al. (2018)). The suitability of the simulation methodology for the urban freight context can be explained by the possibility to examine different concepts in a simple and flexible way without high investments. Using this advantage of simulation, we examine various freight consolidation schemes across several LSPs in this paper.

3.1. Simulation model architecture and input data

In our simulation model, we consider an urban distribution system consisting of a number of LSPs who deliver parcels to business clients in an urban area. Thereby, we model different options for freight consolidation that are evaluated from an economic and traffic perspective. The discrete event simulation model with agent-based elements created for this purpose was developed using AnyLogic 8.2.3. Fig. 2 shows the high-level overview of the simulation model implemented. The model uses several databases from which location data, vehicle and receiver characteristics and GIS-based routing data are loaded. In addition, it is possible to define custom scenarios through a user interface. Based on the receiver database and the demand profiles, transport orders are either generated stochastically or read from a database. At user-defined agent-specific scheduling intervals, all of the open delivery orders from an agent are transferred to a route planning algorithm. For this purpose, we use the Java-based open source toolkit jsprit 1.7.2 (Schröder 2017), which uses a meta-heuristic that is inspired by the works of Schrimpf et al. (2000) and Pisinger and Ropke (2007). This algorithm is one of the core components of the simulation model and solves the corresponding heterogeneous vehicle routing and pick-up-and-delivery problems with time windows that arise during the simulation. The length of a tour is therein restricted by either the weight or volume capacity of the selected vehicle or the maximal allowable tour duration. After routes are generated by the vehicle routing algorithm the routes are returned to the corresponding freight actor and executed under stochastic parameters by the selected vehicles in the simulation. During the execution of tours, loads are either delivered to the final receiver or transferred to the next actor in the transport chain.

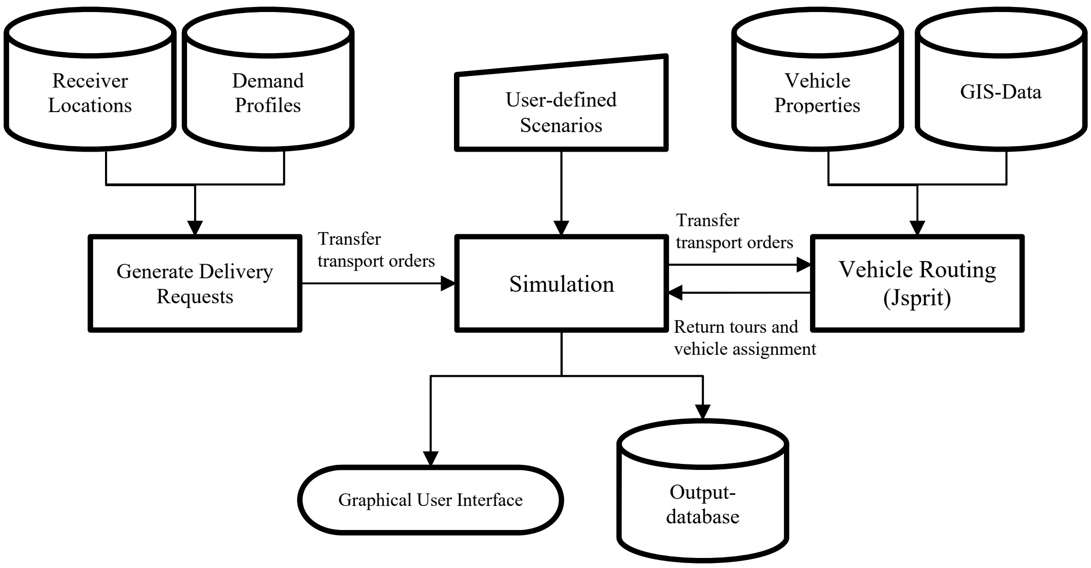

Fig. 2. Simulation model architecture.

In order to evaluate the simulated system, the presented model architecture offers two output options. First, key performance indicators and operational statistics are collected on agents and can be written into a database for further analyses. Second, transport processes and agent state charts are visualized by a graphical user interface that allows validating the model.

3.2. Modeled agents and interactions

Analogously to many other urban freight simulation models, we model a selection of stakeholders and actors as agents. As shown in Fig. 3, the presented simulation model includes 4 types of actors: (1) receivers (business clients) who receive deliveries, (2) LSPs who receive delivery orders from receivers, (3) UCCs and (4) MCCs who can perform the last mile deliveries on behalf of the LSPs.

The first one of the main agent types of the model is the receiver agent which generates the demand for deliveries and is the recipients of the shipment. Inspired by the works of van Heeswijk et al. (2017), receiver agents are characterized by different demand profiles that consist of the following properties (1) average order volume, (2) average weekly order frequency, and (3) number of preferred LSPs. Moreover, we set global values regarding the minimum, maximum and average volume and weight of orders for all receivers. Once a receiver generated a delivery order, the order is transferred directly to the selected LSP and the delivered goods are assumed to be available at the LSPs depot on the next morning. The second types of agents are the LSPs who receive delivery orders from the receivers based on a definable market share and probability to be among the list of preferred LSPs of a receiver. Each LSP owns a fleet of vehicles operates a single distribution center from where the deliveries of goods are made. The third and fourth types of agents are the UCC and MCC that can be used by the LSP to transship and consolidate shipments among LSPs. The two agents mainly differ in that the UCC is located on the outskirts of the city and the MCC is located inside the city center. In the same manner, as the LSPs, both agent types also have their own fleets of vehicles. In addition to the described agents, we also model delivery vehicles (e.g. cargo bikes) and delivery orders as agents in the model. On the other hand, other urban stakeholders, such as residents and public administrators have not been implemented in the model, because legal regulations (e.g. working time and urban access regulations) can be set by the simulation user on the graphical user interface before the start of a simulation run and do not change during a simulation run. This approach can be explained by the long-term time horizon of legal regulations. Furthermore, we only look at the transport chain from the LSP depots and do not consider the upstream networks of the LSPs.

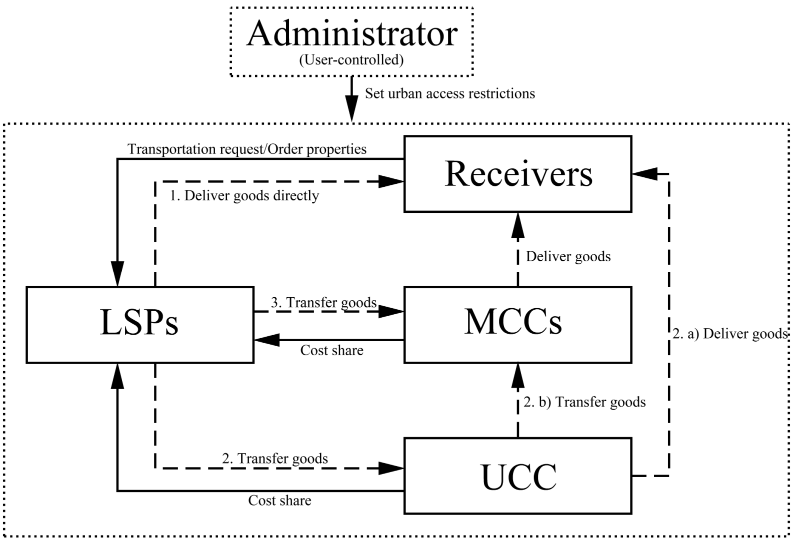

Fig. 3. Interactions among agents.

3.3. Evaluation criteria

In order to assess the impacts of the modeled delivery concepts, we collect statistics on economic and traffic-related metrics during the simulation runs. However, the main focus of the analysis lies on the financial viability of the concepts. For the description of costs, we use a similar notation as described in Elbert and Friedrich (2018). Each tour δ, planned by the route planning algorithm, is executed in the simulation with the travel times and routes from OpenStreetMap and stochastic unloading times. The total time needed to execute a tour δ_{dur} thereby comprises driving, stopping, loading, and possible pauses. The costs of the tour execution consist on the one hand of time-dependent and distance-dependent on the other hand of fixed costs. These, in turn, are determined by vehicle-specific cost rates of the used vehicle type k of the set of available vehicle types N_k. The cost per delivery tour C_δ are obtained using Equation (1)

$$C_\delta = c_k^{dist}\delta_{dist} + c_k^{time}\delta_{dur} + c_k^{fix} \tag{1}$$

where c_k^{dist}, c_k^{time}, and c_k^{fix} describe the distance-, time- and fixed costs of vehicle type $k \in N_k$.

In the further description of the total costs per agent, we distinguish between the LSP and MCC/UCC agents. The set of all tours executed by an LSP $i \in I$ or MCC/UCC $k \in K$ during a month t are denoted by Δ_t^i and Δ_t^k, where I and K represent the set of all LSPs and MCCs/UCCs respectively. The total costs of the UCC and MCC agent types consist of two main cost components. The first cost component is the operating costs $C_t^{k,tr} = \sum_{\delta \in \Delta_t^k} C_\delta$, which describe the total of all tour costs of agent k in the period t. The second cost item are the fixed costs $C_t^{k,f}$ per period t, which are independent of the transshipped volumes and account for costs of the facility. In conclusion, the total costs of the UCC and MCC agent types are summarized as in Equation (2).

$$C_t^k = C_t^{k,tr} + C_t^{k,f} \tag{2}$$

The total costs of the LSPs also consist of two cost components. In contrast to the MCC/UCC, however, these do not include any fixed costs, but proportional shares of the total costs of each used MCC/UCC in period t. These proportional shares result from the number of parcels $n_{t,k}^i$ transshipped by an LSP i at an MCC/UCC k and the total quantity of packages n_t^k of an MCC/UCC in t. This is reflected in the total cost function of the LSPs as shown in Equation (3).

$$C_t^i = C_t^{i,tr} + \sum_{k \in K} C_t^k \frac{n_{t,k}^i}{n_t^k} \tag{3}$$

With regard to the ecological and traffic effects of urban deliveries, we refrain from determining precise emission effect for simplicity. Instead, we measure the number of kilometers driven per vehicle type. This information could subsequently be used to estimate the emissions and transport impacts per scenario.

4. Simulation case study: Frankfurt

4.1. Case study overview

In order to test the developed simulation model and investigate different cargo-bike-based logistics systems, a case study is conducted. For this purpose, we have chosen the city of Frankfurt am Main, which is with over 730 000 inhabitants is the fifth largest city in Germany. Similar to most other major cities in Europe, urban logistics plays an important role in Frankfurt for both the LSPs and the city's administration. Thus, in the course of two pilot projects, two LSPs each introduced an MD for transshipping deliveries onto cargo bikes in Frankfurt.

In our case study, we examine the urban parcel deliveries of 4 LSPs and compare different cooperative delivery concepts. Thereby, we focus on the city center of Frankfurt due to the high receiver density and a particular shortage of space in inner-city areas and therefore favorable preconditions for cooperation between several LSPs. In addition, we only consider B2B-shipments, which usually make up the majority of deliveries in city centers. This has also been confirmed for Frankfurt, where Schäfer et al. (2017) found in a field study that 91% of the parcel deliveries in the inner-city are B2B-shipments.

4.2. Data input and network design

As no cooperative logistics concept exists in Frankfurt, we construct our model based on assumptions and data obtained from other studies as well as actual data from Frankfurt (e.g. business locations and vehicle stop times). To determine the possible receivers, we have extracted position data of businesses tagged as shops from 3 postcode areas in Frankfurt from OpenStreetMap. This resulted in more than 450 receivers of whom we filtered out certain shops, such as bakeries and butchers, leaving 400 receivers to be included in the simulation. For the location of the modeled LSPs, we selected existing facilities of 4 large LSPs in the proximity of Frankfurt. With regard to the locations of the MCCs, we first implemented the real location of an MCC. This MCC is located at a parking facility and currently operated by a single LSP. Second, we selected a public space close to the main railway station for a second MCC. This is justified, by the shortage of inner-city logistics spaces, which could lead public authorities to offer spaces (see e.g. Rudolph and Gruber 2017). As for the UCCs on the outskirts of the city, there are no real-life examples in Frankfurt. We have therefore selected two industrial locations in the west and east of Frankfurt. An overview of the entire network is shown in Fig. 4.

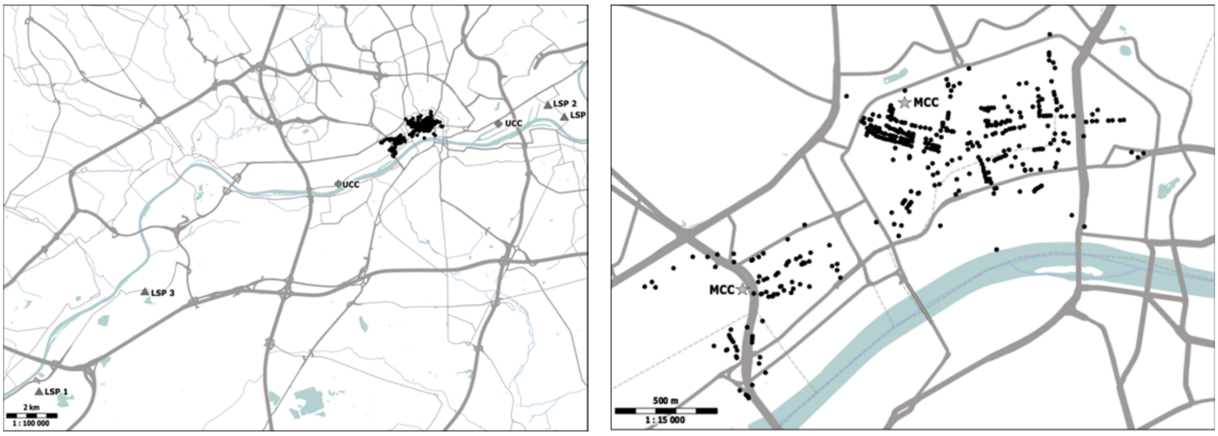

Fig. 4. Overview of the considered network (left and Frankfurt city center (right) with the receiver locations (black dots), UCC locations (grey diamond), MCC locations (grey star), and LSP locations (grey triangle) (Map data copyrighted OpenStreetMap Contributors).

Next, we describe the properties of the receivers and parcels. Based on a study by Schäfer et al. (2017), in which the parcel deliveries of 4 LSPs in Frankfurt were accompanied and analyzed for different district types (e.g. city, residential, industrial area), we set the average number of parcels per customer and LSP delivery to 2.2 parcels. Furthermore, we assume the range of parcels per customer and LSP delivery to be between 1 and 5 parcels. In addition, based on a survey conducted in Nuremberg by Bogdanski (2012) which showed that B2B-customers receive an average of 5.4 parcel deliveries per week, we assume that the total deliveries per week and receiver follow a triangular distribution with an average value of 5.4. Due to the lack of market share data for B2B customers in Frankfurt, we assume that each of the 4 LSPs has the same market share and thus probability to receive an order.

Regarding the average weight and volume of parcels, there is varying data in the literature. Arvidsson and Pazirandeh (2017) report an average weight of 4.0 kg and volume of 0.0195 m³ from a real data set of a Swedish LSP. The report of (ADEME 2004) from an UCC in La Rochelle states in contrast a much larger average parcel weight of 14.31 kg and volume of 0.106 m³. Bogdanski (2012), on the other hand, reports an average of 7.0 kg (median 5) per parcel. Lastly, the German Parcel and Express Logistics Association specify an average shipment weight of 7.4 kg for 2016 (KE-CONSULT Kurte & Esser GbR 2018a). Based on the usual maximum parcel weight of 31.5 kg and reported values in literature, we model the weight of parcels to range between 0.1 to 31.5 kg and assume a mean of 7.4 kg. Similarly, we set the average parcel volume to 0.063 m³ and define the range from 0.00675 m³ to 0.24 m³.

For the operation of the two-level distribution system including the MCCs, each potential receiver is assigned to the nearest MCC/UCC in the model. This is analog to the practices of the LSPs in Frankfurt, which subdivide delivery regions into smaller delivery areas before route planning (Schäfer et al. 2017). Further, we assume that vans and trucks are pre-loaded by the drivers themselves which impact their working time. Consequently, we include the vehicle loading times to the time-dependent tour cost. Cargo bikes, on the other hand, are loaded several times at the MCC during a working day by the drivers themselves. With regard to the vehicle dwell time for loading and unloading parcels to be delivered to the UCCs and MCCs, we estimate a fixed time of 5 minutes and 1.5 minutes per m³ of parcels loaded or unloaded. This is justified by the assumption that the handling of goods could be performed using standardized containers as for example proposed by Arvidsson and Pazirandeh (2017). To account for additional fixed costs (e.g. structural costs) at the UCCs we assume static costs per day for each UCC. Following Estrada and Roca-Riu (2017) we assume 46 €/day per UCC. For the MCCs we assume that smaller facilities are set up and thus only half the fixed costs of the UCC arise.

Another important aspect of the model is the delivery vehicles. According to a recent study, for the delivery of parcels in German cities, mainly diesel vehicles up to 3.5t of the Euro 5 emission standard or better are used (KE-CONSULT Kurte & Esser GbR 2018b, Bogdanski 2017). Although there exists a variety of vehicles, we assume that all LSPs use the same type of vehicles for deliveries. Thereby, we distinguish between vans and trucks used for deliveries or to supply the possible MCCs/UCCs and cargo bikes in our model. For the delivery van we assume an Iveco Daily 35 C 17V and for the larger truck, we assume a Mercedes Atego 818 L. Based on (ETM 2015), we selected for both vehicle models cost parameters, such as purchase prices, taxes, insurance and tire costs as well as costs for repair and maintenance to estimate the yearly cost of ownership and a cost-rate per kilometer. For both vehicles, we thereby assumed a lifetime of 6 years. To allocate the fixed yearly cost of ownership to a daily cost factor we consider 300 operating days per year. For the hourly vehicle costs, we assume that the driver costs for trucks are higher than for vans due to the required truck driver's license.

Similar to the wide range of delivery vans and trucks, there is also a wide variety of cargo bikes available. For the cargo bikes, we consider a Velove Armadillo four-wheel cargo cycle which has been used for example by DHL, Hermes, and DB Schenker. An overview of all three vehicles and parameters is given in table 3.

Table 3. Vehicle properties.

Vehicle Property	Truck (7.49t)	Van (3.5t)	Electric Cargo Bike
Distance-based cost [€/km]	0.34	0.25	0.043
Time-based personnel cost [€/h]	25	20	15
Fixed cost per usage day [€/d]	55.35	35.17	9.02
Weight capacity [kg]	3400	1350	125
Volume capacity [m³]	28	12	1
Routing	Car	Car	Bicycle

In addition to the selection of vehicles, the duration of the stops is an important model parameter. There are varying estimates of stop durations during parcel deliveries. For example, Arnold et al. (2018) assume 2.5 minutes per stop. Schäfer et al. (2017) found out that LSPs in Frankfurt calculate with 3 minutes per stop. However, often deliverers combine several deliveries to different receivers in one stop in order to avoid finding another parking space (see e.g. Bogdanski 2017 and Schäfer et al. 2017). Results from Schäfer et al. (2017) show, that more than 75% of the stops in the city center of Frankfurt take more than 3 minutes. In fact, only 66.8% of the stops are less 10 minutes. In our model try to account for the aggregation of different receivers per stop by assuming that vans are not moved if the next receiver is within a 30-meter walking distance of the current parking position. As a result, we assume the basic stopping time to follow a triangular distribution with a minimum and maximum stop time of 2 and 8 minutes and a mean of 3 minutes. For each additional receiver visited within a stop we add 2 additional minutes.

In contrast to vans, cargo bikes have much fewer problems finding a stopping place and can, therefore, drive directly from customer to customer. It is for this reason, that we assume shorter stop times of only 2 minutes per receiver.

4.3. Analyzed scenarios

As shown in the literature overview, a number of cargo-bike-based urban logistics concepts exist. The aim of this study is to analyze how cargo bikes can be integrated into different consolidation schemes across several LSPs. For the comparison of different cargo-bike-based logistics schemes, we set up four scenarios to be simulated. Therein we consider independent LSP operations by vans as well as cooperative logistics concepts, where deliveries are consolidated. Each is simulated for 20 runs and each simulation run represents a period of 7 days. Following four basic scenarios are formulated and tested:

- Scenario 1 (S1): Independent delivery by vans and trucks from the LSP depots
- Scenario 2 (S2): LSPs transship their deliveries to the nearest UCC which uses vans and trucks
- Scenario 3 (S3): LSPs transship their deliveries to the nearest UCC which distributes the deliveries to the MCCs and onto cargo bikes
- Scenario 4 (S4): LSPs transship their deliveries to the MCCs which operates cargo bikes

For scenarios S1 and S2, we further propose two additional scenarios S1 b) and S2 b), in which motorized vehicles are only allowed to deliver goods to the city center between 8:00 and 11:00.

5. Results and discussion

In this section, we present the results of the simulated case study. We first look at the financial impact of the scenarios studied and then examine the impact on the kilometers traveled per vehicle type.

5.1. Financial analysis

The financial analysis of the four scenarios presented in Fig. 5 shows that although all 4 LSPs have the same market share, different costs arise. Second, it can be noted that LSP 1 and 4, whose depots are located somewhat further from the city center, have higher costs than LSP 2 and 4, which are located close to the city center, in all scenarios studied.

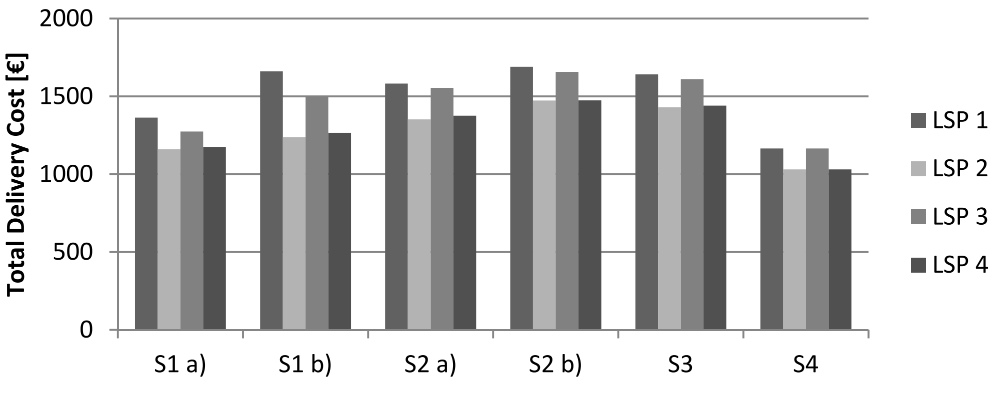

Fig. 5. Cost comparison between the six scenarios.

Comparing the independent deliveries of the LSPs with the deliveries using the UCCs in S2 a), it can be seen that the usage of the UCCs leads to higher costs. The low cost-attractiveness of using the UCCs could be attributed to the relatively large number of stops per LSP (>100 per day) and high receiver density in the studied area. These factors have also been identified to decrease the cost-attractiveness of UCCs by Janjevic and Ndiaye (2017). Furthermore, a large portion of fixed vehicle costs to deliver to the UCCs remain, when the UCCs are used. In S4, where the MCCs are used, the LSPs achieve slightly lowest costs. This is due to the consolidation advantages as well as the shorter stop times and lower costs of the cargo bikes. Also, in contrast to the UCCs, we assume half the fixed costs per day for the MCCs, which is mainly due to the lower space requirements of MCCs. A further comparison of the scenarios shows that S3 leads to the highest costs due to the double handling of goods both at the UCCs and MCCs and higher fixed costs due to both the UCCs and MCCs. It can be concluded that the consolidation and cargo bike advantages are not sufficient to compensate for these additional costs and thus the two-level concept is not advisable for the studied case.

In the event that delivery times are restricted by time windows, the costs of LSPs increase in S1 b) as expected, making the use of MCCs S4 more attractive. At the same time, however, the costs for the UCC in S 2b) are also slightly increasing and still remain higher than the costs of the independent deliveries in S1 b). Furthermore, S3 becomes slightly cost-attractive for LSP 1 and 3, but leads to significantly higher costs for LSP 2 and 4, who are located closer to the city center. Overall, the results indicate that the usage of MCCs and cargo-bikes can be a financially viable option for LSPs. These benefits would be even further enhanced by the introduction of additional traffic restrictions from which the cargo bikes would be exempt.

5.2. Traveled kilometers

The analysis of the traveled kilometers per vehicle type in Fig. 6 shows, as expected, that when using cargo bikes, the traveled kilometers of the trucks decrease significantly. However, a large proportion of the traveled kilometers remains, as the LSPs still have to drive into the city from their depots, which in some cases are relatively far away. Nevertheless, it is evident that cargo-bike-based scenarios can contribute to reducing motorized traffic and thus traffic-induced emissions. Comparing the two-level distribution system in S3 with the one-level system in S4, only slight increases can be seen. This can be explained by possible detours as a result of additionally routing the deliveries via the UCCs. Furthermore, the comparison of S1 a) and S2 a) reveals, that the usage of the UCCs only reduces the number of vehicle kilometers marginally. However, when time windows are introduced, it becomes apparent, that the LSPs switch to use the smaller vans in S1 b), which sharply increases the total kilometers traveled. Meanwhile, if the UCCs are used in S2 b) the usage of vans increases too, but the increase in the total kilometers traveled is significantly smaller.

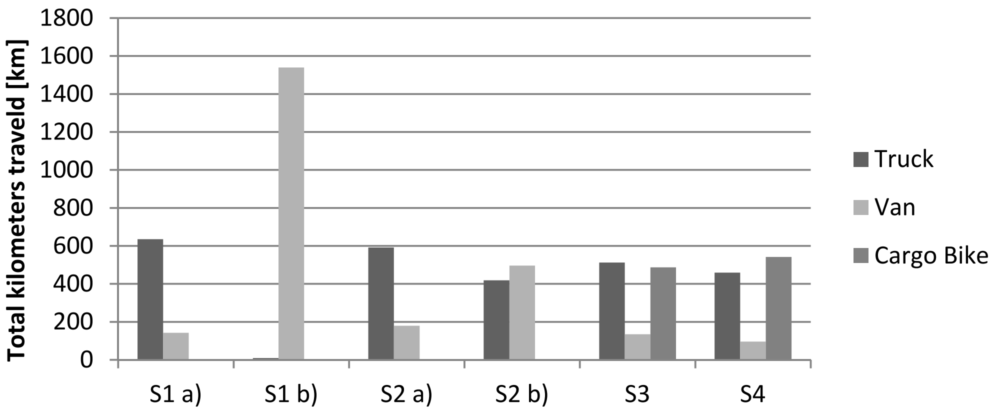

Fig. 6. Comparison of the average total kilometers traveled per vehicle type.

6. Conclusion

In this work, a hybrid agent-based and discrete event simulation model to evaluate cargo-bike-based urban deliveries is presented. Motivated by the growing number of options and concepts for urban goods deliveries, the presented simulation model allows LSPs and public authorities to analyze several consolidation concepts under varying problem settings in a risk-free environment.

Contrary to most previous works related to cargo bikes in urban logistics and pilot studies, we focus on the consolidation of goods among multiple LSPs. By conducting four scenarios we analyze both the economic viability as wells as the traffic impact of integrating cargo bikes into urban consolidation schemes. The results show that both the use of cargo bikes and the cooperation between the LSPs can be promising from both an environmental and financial point of view. However, our study focuses on urban parcel deliveries of B2B-shipments in the city center of Frankfurt am Main. For the generalization of our results to other cities and countries, however, the specific characteristics of these places would have to be taken into account. For example, each city has its own size, road infrastructure, demand structure, and local regulations, which influence the implementation of the cargo-bike-based urban logistics concepts. In addition, the cost factors for rent and labor can vary substantially depending on the country and city under consideration and might affect the financial viability of the considered concepts decisively. Also, company-specific factors, such as the order structure (e.g. share of B2B-customers) and companies' depot locations have an impact on the operations and consequently costs of the concepts.

In our simulated case study, we tried to use realistic data based on previous studies and observations from Frankfurt and model the LSPs' operations close to reality. However, some assumptions are made to create the simulation. We assume that all parcels fit into the cargo compartment of the modeled cargo bikes. In practice, parcels might be larger and thus cargo bikes cannot fully substitute vans, due to their smaller volume. Depending on the share of parcels that can't be transported by cargo bikes, the benefits of using a cargo-bike-based concept could be reduced.

Furthermore, several assumptions had to be made due to the lack of detailed data. For example, it is still uncertain as to what percentage stop times will be reduced compared to vans when using cargo bikes or how much travel time could be saved due to being less impacted by traffic jams. Additionally, we concentrated on our case study only on deliveries and left pick-ups of goods out of the analysis. In practice, LSPs usually also pick up parcels during their delivery tours. Thus, in further studies, pick-ups could be included as well. However, from a competitive point of view pick-ups could be particularly problematic (Bogdanski 2017). Lastly, in our model, we assume that all 5 LSPs are willing to fully cooperate together. In reality, however, this is not necessarily the case, as there is a great deal of competition between LSPs. Nevertheless, first steps towards cooperation across LSPs have already been made as shown in pilot studies.

References

Agence de l'Environnement et de la Maîtrise de l'Énergie (ADEME), 2004. Analyse Comparative des Systèmes Logistiques Rochelais et Monégasques – ´ Eléments Pour un Guide Méthodologique. https://www.ademe.fr/espaces-logistiques-urbains-monaco-rochelle-elements-guide-methodologique. Accessed April 4th, 2018.

Allen, J., Browne M., Woodburn A., Leonardi J., 2012. The Role of Urban Consolidation Centres in Sustainable Freight Transport. Transport Reviews 32.4, 473–490.

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 25.2, 345–376.

Arnold, F., Cardenas, I., Sörensen, K., Dewulf, W., 2018. Simulation of B2C e-commerce distribution in Antwerp using cargo bikes and delivery points. European Transport Research Review 10.1, 135.

Arvidsson, N., Pazirandeh, A., 2017. An ex ante evaluation of mobile depots in cities. International Journal of Sustainable Transportation 11.8, 623–632.

Bogdanski, R., 2012. Umfrageergebnisse zur Belieferungssituation in der Nürnberger Innenstadt mit Kurier- und Expresssendungen (KEP) unter Gewerbetreibenden und KEP-Dienstleistern im September 2012. Industrie- und Handelskammer Nürnberg für Mittelfranken. <https://www.ihk-nuernberg.de/de/media/PDF/Standortpolitik-und-Unternehmensfoerderung/Logistik/umfrageergebnisse-zur-belieferungssituation-in-der-nuernberger-innenstadt-mit-k.pdf>. Accessed July 8th, 2018.

Bogdanski, R., 2017. Innovationen auf der Letzten Meile – Bewertung der Chancen für eine Nachhaltigen Stadtlogistik von morgen. Bundesverbandes Paket und Expresslogistik e. V. (BIEK).

Bundesverband Paket und Expresslogistik e. V. (BIEK), 2018. Lieferverkehr mit Lastenrädern nachhaltig gestalten. https://www.biek.de/index.php/ pressemitteilung_detailansicht/items/komodo-projektstart.html. Accessed July 13th, 2018.

Dablanc, L. 2011. Transferability of Urban Logistics Concepts and Practices from a Worldwide Perspective – Deliverable 3.1 – Urban Logistics Practices – Paris Case Study. http://www.transport-research.info/sites/default/files/project/documents/20130703_154506_25800_D3.1_ casestudyParisFrance.pdf. Accessed July 13th, 2018.

Elbert, R., Friedrich, C., 2018. Simulation-based Evaluation of Urban Consolidation Centers Considering Urban Access Regulations. In Rabe, M., et al., 2018 Winter Simulation Conference (WSC), Gothenburg, Sweden, 2018, 2827-2838.

Estrada, M., Roca-Riu, M., 2017. Stakeholder's profitability of carrier-led consolidation strategies in urban goods distribution. Transportation Research Part E: Logistics and Transportation Review 104, 165–188.

EuroTransportMedia Verlags- und Veranstaltungs-GmbH (ETM) 2015. lastauto omnibus Katalog 2015. Stuttgart.

Fikar, C., Hirsch, P., Gronalt, M., 2017. A decision support system to investigate dynamic last-mile distribution facilitating cargo-bikes. International Journal of Logistics Research and Applications 21.3, 300–317.

Gruber, J., Kihm, A., 2016. Reject or Embrace? Messengers and electric cargo bikes. Transportation Research Procedia 12, 900–910.

Gruber, J., Kihm, A., Lenz, B., 2014. A new vehicle for urban freight? Research in Transportation Business & Management 11, 53–62.

Hofmann, W., Assmann, T., Neghabadi, P. D., Cung, V.-D., Tolujevs, J., 2017. A simulation tool to assess the integration of cargo bikes into an urban distribution system. The 5th International Workshop on Simulation for Energy, Sustainable Development & Environment. Barcelona, Spain, 11–20.

Janjevic, M., Ndiaye A., 2017. Investigating the Theoretical Cost-relationships of Urban Consolidation Centres for Their Users. Transportation Research Part A: Policy and Practice 102, 98–118

Jlassi, S., Tamayo, S., Gaudron A., 2018. Simulation Applied to Urban Logistics: A State of the Art. In: Taniguchi, E., Thompson, R. G. (Ed.) City Logistics 3: Towards Sustainable and Liveable Cities. ISTE Ltd, London, pp. 65.

KE-CONSULT Kurte & Esser GbR, 2018a: BIEK-Kompendium „Zahlen, Daten, Fakten zum Kurier-, Express-, Paketmarkt“ Teil 1: Transportaufkommen und Durchschnittliches.

KE-CONSULT Kurte & Esser GbR, 2018b: BIEK-Kompendium „Zahlen, Daten, Fakten zum Kurier-, Express-, Paketmarkt“ Teil 3: Fahrzeugbestand nach Emissionsklassen und nach Antriebs- und Kraftstoffarten.

Koning, M., Conway, A., 2016. The good impacts of biking for goods: Lessons from Paris city. Case Studies on Transport Policy 4.4, 259–268.

Leonardi, J., Browne, M., Allen, J., 2012. Before-After Assessment of a Logistics Trial with Clean Urban Freight Vehicles. Procedia - Social and Behavioral Sciences 39, 146–157.

Maes, J., Vanelslander, T., 2012. The Use of Bicycle Messengers in the Logistics Chain, Concepts Further Revised. Procedia - Social and Behavioral Sciences 39, 409–423.

Marujo, L. G., Goes, G. V., D'Agosto, M. A., Ferreira, A. F., Winkenbach, M., Bandeira, R. A. M., 2018. Assessing the sustainability of mobile depots. Transportation Research Part D: Transport and Environment 62, 256–267.

Melo, S., Baptista, P., 2017. Evaluating the impacts of using cargo cycles on urban logistics. European Transport Research Review 9.2, 61.

Navarro, C., Roca-Riu, M., Furió, S., Estrada, M., 2016. Designing New Models for Energy Efficiency in Urban Freight Transport for Smart Cities and its Application to the Spanish Case. Transportation Research Procedia 12, 314–324.

Nocerino, R., Colorni, A., Lia, F., Luè, A., 2016. E-bikes and E-scooters for Smart Logistics. Transportation Research Procedia 14, 2362–2371.

Pisinger, D., Ropke S., 2007. A General Heuristic for Vehicle Routing Problems. Computers & Operations Research 34.8, 2403–2435.

Rudolph, C., Gruber, J., 2017. Cargo cycles in commercial transport. Research in Transportation Business & Management 24, 26–36.

Schäfer, P., Schocke, K.-O., Höhl, S., Quitta, A., Kämmer, A., Blume, S., Brandt, J., 2017. Wirtschaftsverkehr 2.0 - Analyse und Empfehlungen für Belieferungsstrategien der KEP-Branche im innerstädtischen Bereich. Frankfurt University of Applied Sciences. 2017.

Schliwa, G., Armitage, R., Aziz, S., Evans, J., Rhoades, J., 2015. Sustainable city logistics - Making cargo cycles viable for urban freight transport. Research in Transportation Business & Management 15, 50–57.

Schrimpf, G., Schneider, J., Stamm-Wilbrandt, H., Dueck, G., 2000. Record Breaking Optimization Results Using the Ruin and Recreate Principle. Journal of Computational Physics 159.2, 139–171.

Schröder, S., 2017. “jsprit: 1.7.2”. <https://github.com/graphhopper/jsprit>. Accessed July 4th, 2018.

Van Heeswijk, W., Larsen, R., Larsen, A., 2017. An Urban Consolidation Center in the City of Copenhagen: a Simulation Study. BETA working papers, no. 523, TU Eindhoven, Research School for Operations Management and Logistics (BETA), Eindhoven.

Verlinde, S., Macharis, C., Milan, L., Kin, B., 2014. Does a Mobile Depot Make Urban Deliveries Faster, More Sustainable and More Economically Viable. Transportation Research Procedia 4, 361–373.

United Nations, 2015. World Urbanization Prospects: The 2014 Revision. Technical report, Department of Economic and Social Affairs, Population Division, New York.