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SIMULATION-BASED EVALUATION OF URBAN CONSOLIDATION CENTERS CONSIDERING URBAN ACCESS REGULATIONS

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ABSTRACT

The negative effects of urban freight transports, such as air quality problems, road congestion, and noise emissions lead in many cities to major difficulties. A widely studied measure to reduce these negative effects are Urban Consolidation Centers (UCCs), which aim to bundle freight flows to reduce the number of urban freight transports. However, many projects showed that the additional costs of UCCs often made it unattractive for carriers to participate in such schemes. This paper presents an agent-based simulation to assess the impact of urban access regulations on the cost-attractiveness of UCCs for carriers. A case study inspired by the Frankfurt Rhine-Main area is presented to compare deliveries of a group of carriers with and without a Urban Consolidation Center under various urban access scenarios. The simulation shows that regulations increase the cost-attractiveness of UCCs for carriers to varying degrees while increasing the overall traffic volume.

1 INTRODUCTION

Today, more than 54% of the world's population live in urban areas and the share of the world's urban population is expected to increase to 60% by 2030 (United Nations 2015). Along with the growth in urban population, the demand for urban goods and thus urban freight transports increases steadily. While urban freight transport poses an inevitable part in the economic and social system of a city, the growth in urban freight transport is accompanied by negative impacts on the urban population and attractiveness of the urban areas it serves (Ogden 1992; Crainic et al. 2009).

Since the early 1990s, managing urban freight has become a key challenge in urban management and led to the rise of city logistics initiatives in research and practice (Allen et al. 2012; Crainic et al. 2009; Browne et al. 2005). Much of this research and many schemes in practice focus on reducing the negative impacts associated with urban freight transport (e.g. congestion, pollutant emissions, noise) by means of consolidation and collaboration strategies without negatively affecting the economic and social activities within the urban area (van Duin et al. 2012; Crainic et al. 2009; Rabe et al. 2016). In this context, particular attention has been given to Urban Consolidation Centers (UCCs) which are a widely studied measure in city logistics. The basic principle of a UCC is to reduce the number of urban freight transports by bundling freight in a logistics facility in the proximity of an urban area and transshipping it onto vehicles with increased load factors (Allen et al. 2012). Although more than 100 implementations of UCCs have been reported in the literature, many projects failed due to low participation and therefore financing problems (Allen et al. 2012).

A critical factor for the success of UCC schemes are government policies (see e.g. Marcucci and Danielis 2008; van Duin et al. 2012; Ville et al. 2013). Local authorities pursue the goal to make freight transport more sustainable and therefore support the realization of UCCs in different ways. Besides financial

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support in form of subsidies, regulatory measures are often adopted to promote the use of the UCC (Allen et al. 2012; Browne et al. 2005; Ville et al. 2013).

In practice, many cities already have some form of urban access regulations to regulate the traffic of heavy goods vehicles regardless of the existence of a UCC. Especially delivery time windows within city centers and pedestrian zones, in particular, represent a popular measure to regulate urban freight deliveries (Russo and Comi 2010; Quak and de Koster 2009). In addition, as a consequence of continuing air quality problems in urban areas, further measures such as for example truck bans and congestion charges are either already implemented or being discussed in many places.

Although UCCs and urban access regulations are intertwined through similar goals and interference, only relatively little is known about the interrelations between both. The aim of this paper is to study the cost-attractiveness of carrier-led UCCs under various urban access regulations. For this reason, we develop an agent-based simulation model to examine the question of how urban access regulations influence the cost-attractiveness of UCC schemes. In contrast to previous works, we consider an entire region, where carriers have to perform deliveries to receivers within a city and smaller surrounding municipalities. Thereby, only transport orders located in the UCC service area can be assigned to a UCC. By using a GIS-based street network and actual retailer and carrier locations we assess the impact of a UCC and urban access regulations on the operations of carriers in an entire region, including both urban and non-urban deliveries.

The outline of this paper is as follows: In Section 2 we briefly discuss the related literature on UCCs and urban access regulations. In Section 3 we present our simulation model on carrier-led UCCs and the implementation of urban access regulations. Section 4 describes the studied case and experimental setup. The results of the model and case study are discussed in Section 5. Finally, Section 6 concludes and provides pointers for future research.

2 RELATED LITERATURE

Aspects of particular importance are the costs and financial viability of UCCs. Besides the theoretical benefits of UCC schemes, the inclusion of a UCC into the urban transport chain is accompanied by both set up costs for the UCC as well as additional operational costs caused by the transsshipment such as extra handling costs. Thus, in order to be an attractive alternative for carriers, the costs of independent last mile deliveries have to exceed the additional costs related to the UCC (Marcucci and Danielis 2008). Confirming this theoretical reasoning, Nordtømme et al. (2015) also identify the financial viability as the main barrier to establish a UCC in the context of a planned UCC implementation in Oslo.

Existing works analyze different factors influencing the possible costs savings of UCCs and consequently its cost-attractiveness to receivers and carriers. Roca-Riu et al. (2016) develop an analytic model featuring carriers with different market shares to analyze the potential cost savings of UCCs. The model results reveal little impact of different market shares on the operational savings of a UCC. However, they point out the importance of other parameters, such as vehicle capacities and distances of depots and the UCC to the service area. Battaia et al. (2014) analyze the level of carrier participation at UCCs through game theory and simulation. For this purpose, they aim to determine the conditions which lead to operational savings for carriers. Their results also show a strong influence of the distances and locations of the UCC and carrier depots relative to the city center. Janjevic and Ndiaye (2017b) provide an analytic model for the estimation of urban delivery costs and evaluation of the cost-attractiveness of UCCs. With their model, they examine the cost structure of UCCs and factors, such as delivery characteristics, influencing the cost-attractiveness of UCCs in a case study. Estrada and Roca-Riu (2017) also investigate the financial viability of UCC schemes. On the basis of an analytic cost model, they identify vehicle costs and other vehicle-related parameters to have only a minor impact on the financial viability of UCCs. However, they point out that a critical density of receivers exists that makes routing via the UCC cost-attractive for carriers.

Quak and Tavasszy (2011), as well as Ville et al. (2013) identify the presence of government policies as an essential component of viable UCCs. By issuing regulations or urban access restrictions the usage of UCCs can be encouraged. In this context, van Duin et al. (2012) coin the notation of policy-oriented modeling which aims to retrace urban truck movement in the presence of different government policies to assess its implications. Following this characterization, van Duin et al. (2012) investigate the contribution of policy measures to the successful operations of a UCC in an artificial city network with the aid of an agent-based simulation. Thereby, they examine the impacts of congestion, dynamic toll rates and subsidies by a local authority on the dynamic usage of UCCs. Their results indicate a little impact of different toll rates and a strong dependence on subsidies for UCCs to be viable. Tamagawa et al. (2010) also propose a multi-agent model for evaluating the impacts of road tolls and truck bans on different stakeholders in a test city network. Thereby, they differentiate between privately owned motorways and publicly owned roads. Their results show that a reduction in motorway tolls in combination with truck bans offers a large potential to reduce negative environmental effects. Marcucci and Danielis (2008) by contrast conducted a stated-preference study to investigate the decision-making by receivers and transport operators regarding the use of a UCC. They show that among other policies and subsidies, zone-based access fees and parking restrictions have a positive effect on the UCC usage probability. Also, Wangapisit et al. (2014) examine the frequency of UCC usage with regard to the level of carrier subsidies and parking fees which incur additional costs for carriers but not for the UCC. With the aid of an agent-based simulation, they show a positive effect of subsidies and parking management policies on the usage of the UCC.

Van Heeswijk et al. (2017) provide an agent-based simulation model to assess the user base of a UCC under different delivery scenarios and government policies. By considering delivery time windows, zone-based access fees and subsidies, they study the environmental and financial effects of numerous schemes using the city of Copenhagen as an example. Through a sensitivity analysis, they show that delivery time windows wider than two hours as a standalone measure do not contribute to the attractiveness of UCC schemes for carriers. Estrada and Roca-Riu (2017) also consider delivery time windows for carriers from which the UCC that uses cargo bikes is exempt. In their case study, they show that the total distance traveled and required fleet size for carriers increases with the implementation of delivery time windows. Thus, the cost advantage of the UCC with exempt vehicles increases under the presence of delivery time windows. Simoni et al. (2018) analyze a scenario where access restrictions only allow electric vehicles and cargo bikes to enter the UCC service area. Their results indicate as expected a considerable reduction in vehicle emissions. Besides in the context of UCCs, the implications of urban access regulations and policies have also been studied in a broader sense in literature from different points of view. Most notably, Quak and de Koster (2009) investigate the environmental and financial impacts of delivery time windows and vehicle restrictions on the logistics operations of two types of retailers with nationwide distribution to their stores. Similar to Estrada and Roca-Riu (2017), their results indicate an increase in the total distance traveled and thus increased delivery costs and emissions.

The overview of the related works shows that the cost-attractiveness of UCCs has been a widely-studied topic in the context of UCCs. Therein, also access regulations received some attention and have been confirmed to increase the cost-attractiveness of UCCs. However, many of the presented studies rely on simplified small test networks and extensive model assumptions. Moreover, so far it has not been taken into account that in the course of a delivery tour carriers not only perform deliveries in one urban center but often also deliver goods to suburbs and other cities within the same region. In addition, it is usually assumed that carriers and UCCs operate homogeneous fleets of delivery vehicles. However, in reality transport operators often have a mixed fleet of vehicles. The contribution of this study is to assess the impact of urban access regulations on the cost-attractiveness of UCCs for carriers with both urban and non-urban deliveries and heterogeneous fleets.

3 METHODOLOGY

Simulation is a well-established methodology for analyzing urban logistics schemes and public policies (Maggi and Vallino 2016). This can be explained by the advantages of simulation compared to mathematical modeling approaches which often cannot account for the complexity and heterogeneity of urban logistics systems (Taniguchi et al. 2001). By using simulation, we aim to identify the impact of urban access regulations on the cost-attractiveness of carrier-led UCCs. For this purpose, we study several access regulations with and without the usage of a UCC and investigate the effects on its cost-attractiveness for the participating carriers. Contrary to other works, we also consider transports to receivers outside of the city where the last-mile delivery cannot be outsourced to the UCC.

3.1 Simulation Model Outline

In our simulation model, we assume an area-based, carrier-led UCC that focuses on B2B urban freight transport. At the core of the simulation model lies a discrete event simulation with agent-based elements. The simulation model was implemented using the simulation software AnyLogic 8.2.3 which offers discrete-event, system dynamics and agent-based modeling techniques. Similar to the framework of van Heeswijk et al. (2016) and the works of van Duin et al. (2012), the simulation model includes several urban stakeholders as agents. Namely, these agents are a UCC, receivers, and carriers. Due to the agent-based approach of AnyLogic, we further model delivery vehicles, transport orders, and delivery tours as agents as well. The often proposed administrator agent has not been explicitly modeled since urban access regulations are set by the simulation user on a scenario basis and do not change during a simulation run. This is justified by the usual long-term focus of governmental policies. Additionally, it is assumed that all cost factors remain static during each simulation run and no economies of scale are realized based on the stochastic order volumes.

3.2 Interactions between Agents

The roles and interactions between the agents are an essential aspect of the simulation model. An overview of the interactions among the agents is visualized in Figure 1. The starting point of the simulation runs are the receivers which stochastically place transport requests at the carriers. We thereby assume that all goods are in stock at the carriers' depots and thus do not consider shippers, where the goods have to be picked up. In contrast to other approaches, the receivers can be primarily distinguished by being either located within the service area of the UCC or outside of it. Only receivers within the UCC service area can receive their delivery through the UCC. Furthermore, analogously to van Heeswijk et al. (2017), receivers can exhibit different demand characteristics and vary in their order volume, number of order moments per week and number and choice of preferred carriers. The carriers, in turn, possess different market shares, a fleet of vehicles and a depot from where they operate. Based on the predefined choice of participation at the UCC, the carriers either deliver to all receivers in the region directly or drop their urban deliveries at the UCC. The UCC only receives shipments for receives within its service area and performs the last-mile delivery to the urban receivers using its own fleet of vehicles. Because we only assess the cost-attractiveness of the UCC towards the carriers, only monetary flows between these two agents are represented in the model. Hence, the shipping prices charged to the receivers by the carriers are not taken into account in the analysis. Lastly, to represent governmental policies by local administrators, the following urban access regulations can be applied in each simulation run:

- Delivery time windows;
- Zone-based access fees;
- Truck restrictions (e.g. no trucks >7.5t).

In addition to the described agents above, we want to briefly outline the remaining agents. The delivery vehicles are either owned by the UCC or one of the carriers and possess specific capacities and cost characteristics. A transportation order describes a request from a receiver to a carrier to ship a specified load to its location. After performing the vehicle routing, delivery tours consisting of transportation orders are assigned to delivery vehicles and subsequently executed. Following the tour completion, the delivery vehicles return to their home depot and various tour statistics are generated.

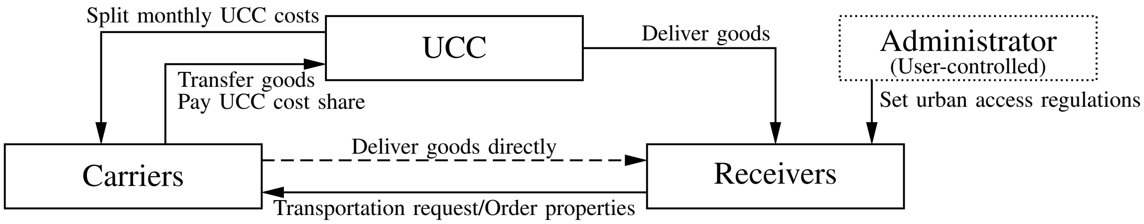


Figure 1: Interactions between the agents.

3.3 Cost Functions and KPI

Several cost functions are implemented to quantify the effects of the urban access regulations on the cost-attractiveness of the UCC. For the description of costs, we use a similar notation as proposed in van Heeswijk et al. (2017). Table 1 gives an overview of the considered costs and notations used.

Table 1: Overview of cost notations.

Notation	Description
C_t^{UCC}	Total UCC cost in month t (€/month)
$C_{t,i}^{Car}$	Total costs of carrier i in month t (€/month)
$C_t^{UCC,f}$,$C_{t,i}^{Car,f}$	Fixed costs of the UCC or carrier i in month t (€/month)
$C_t^{UCC,tr}$,$C_{t,i}^{Car,tr}$	Transport costs of the UCC or carrier i in month t (€/month)
$C_t^{UCC,h}$	Handling costs of the UCC in month t (€/month)
C_δ	Tour operating cost of tour δ (€/tour)
c_k^{dist}	Distance-based cost rate per kilometer for deliveries with vehicle type $k \in N_k$ (€/km)
c_k^{time}	Time-based cost rate per hour for deliveries with vehicle type $k \in N_k$ (€/h)
c_k^{toll}	Costs for entering the urban area per day with vehicle type $k \in N_k$ (€/day)

A main cost component of the simulation model are transport costs. Both carriers and the UCC make routing decisions for the last-mile distribution which affect their transport costs. For solving the underlying heterogeneous vehicle routing problem with time windows, 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).

During the simulation, each generated tour δ is executed under static travel and stochastic unloading times. The set of all tours executed during a month t are denoted by Δ_t^{UCC} for the UCC and $\Delta_{t,i}^{Car}$ for a carrier $i \in I$, where I represents the set of all carriers. The total duration δ_{dur} of a tour consists of driving, unloading, and possible break and waiting times. The cost functions per time and distance of a tour depend on the used vehicle type k of the set of available vehicle types N_k. The costs per tour C_δ are formulated, as

$$C_\delta = c_k^{dist}\delta_{dist} + c_k^{time}\delta_{dur} + c_k^{toll}\rho_\delta,$$

where c_k^{dist}, c_k^{time}, and c_k^{toll} denote the distance-, time- and toll-based costs of vehicle type $k \in N_k$ and $\rho_\delta \in \{0,1\}$ constitutes a binary variable to represent whether the tour includes deliveries to the urban area or not. The overall monthly costs of the UCC are comprised by three main cost components. The transportation costs $C_t^{UCC,tr} = \sum_{\delta \in \Delta_t^{UCC}} C_\delta$ represent the sum of the costs of all tours Δ_t^{UCC} executed by the UCC within t. The monthly handling costs $C_t^{UCC,h}$ depend on the volumes handled by the UCC in t. Furthermore, fixed monthly costs $C_t^{UCC,f}$ can be assigned to the UCC. Due to the assumption that the UCC does not offer any storage services and because shipments are usually transferred within a day, the inventory costs of shipments are neglected. In summary, the monthly costs of the UCC are formulated as follows:

$$C_t^{UCC} = C_t^{UCC,tr} + C_t^{UCC,h} + C_t^{UCC,f}.$$

Second, we describe the monthly costs for the carriers. Similar to the monthly UCC costs, the costs of a carrier $i \in I$, include transportation costs $C_{t,i}^{Car,tr}$ and possible fixed costs $C_{t,i}^{Car,f}$. In addition, if the carrier participates at the UCC, represented by a binary variable $\gamma_i \in \{0,1\}$, a proportion of the monthly UCC costs is assigned to the carrier i. For simplicity, this proportion is assumed to be only dependent on the share of the number of orders $n_{t,i}^{Car}$ outsourced from carrier i in t of the total number of orders n_t^{UCC} processed by the UCC in t. As result, the following cost function is given for the costs of carrier $i \in I$ in t:

$$C_{t,i}^{Car} = C_{t,i}^{Car,tr} + \gamma_i C_t^{UCC} \frac{n_{t,i}^{Car}}{n_t^{UCC}} + C_{t,i}^{Car,f}.$$

Besides costs, we also measure both the total distances traveled by the UCC and carriers and number of vehicles entering the urban area to give an estimate of the effects on the traffic volume and environmental impacts. However, we refrain from conducting a detailed assessment of emissions due to the focus of this paper being on the financial aspects of UCCs.

4 FRANKFURT CASE STUDY

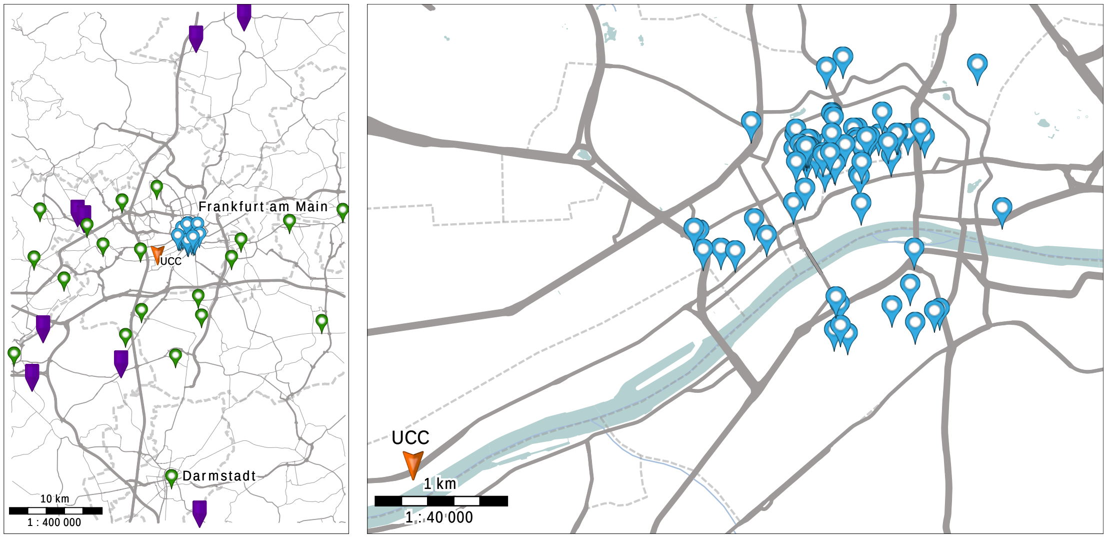
In this section, we describe a case which we used to test the simulation model and assess the impact of urban access regulations on the cost-attractiveness of UCCs for carriers. The area chosen for the case study of the simulation model is the Frankfurt Rhine-Main area. The Frankfurt Rhine-Main area is a polycentric metropolitan region consisting of almost 200 cities, towns and rural municipalities located in the center of Germany. With a total population of more than 5.8 million, it is the third largest metropolitan region in Germany. As a consequence of particulate pollution, a low-emission zone has been established in Frankfurt in 2008.

4.1 Data Collection and Network Design

Since there exists no real-world UCC in the Frankfurt Rhine-Main area, we modeled a fictive UCC using cost factors and data obtained from the related literature. In consequence of the fact that there is only limited or strongly varying data on UCCs and urban freight demand (van Heeswijk et al. 2017), several assumptions regarding the parameters for the simulation study have been made.

In order to generate a network of receivers, we extracted retailer locations in specified areas from the OpenStreetMap and randomly selected a sample to use in the case study. For the UCC service area, 80 retail locations which are located in the city center of Frankfurt were chosen. To account for the carriers' transport operations in the suburbs and surrounding towns, 20 additional municipalities have been selected and represented by one randomly retrieved retailer location each. Although a single UCC might not always be sufficient for a larger city, because of possible detours for carriers to stop at the UCC (Huschebeck and Allen 2005), we modeled for simplicity only a single UCC, which is conveniently located near two motorways in the west of Frankfurt. Similarly to the selection of receivers, we extracted a sample of 8 carrier locations located west, south, and north of the UCC. Due to carriers situated east of Frankfurt facing large detours caused by the need to drive through or around the city center to reach the UCC, we excluded those carrier locations from the selection process. An overview of the selected retail and carrier locations is given in Figure 2.

Based on the selected locations, we created a time- and distance-based origin-destination matrix using the OpenStreetMap-based routing engine Open Source Routing Machine from Luxen and Vetter (2011) as an input for the vehicle routing algorithm and simulation. For modeling urban access regulations and restrictions, we followed real regulations and reports from literature. Regarding the length of delivery time windows, we first analyzed existing delivery time windows in Germany. Second, we compared the duration of reports and scenarios studied in literature to create stricter scenarios. Many pedestrian zones in Germany possess delivery time windows of up to 6 hours. For example, in some parts of Frankfurt's pedestrian zone access is only allowed between 5:00 and 11:00. However, in literature more restrictive



(a) Frankfurt Rhine-Main Area.

(b) Frankfurt city center.

Figure 2: Maps of the Frankfurt Rhine-Main area and Frankfurt city center with the UCC location (orange arrow), carrier depots (purple squares), urban receivers (blue pins) and non-urban receivers (green pins) (Map data copyrighted OpenStreetMap Contributors).

cases can be found. For example, van Duin et al. (2010) report that the French city of La Rochelle only allowed freight delivery vehicles exceeding 3.5t to deliver between 6:00 and 7:30. Similarly, van Heeswijk et al. (2017) report a 2-hour time window for Copenhagen. The second restriction, which we validated with the help of the literature, are zone-based access fees. Currently, there exists no zone-based access fee in Frankfurt. However, this measure has been frequently studied in literature and applied or discussed elsewhere in Europe. For instance, the Swedish cities of Gothenburg and Stockholm introduced access fees up to SEK 60 and 105 (approximately 5.95€ and 10.40€) per vehicle and day. Similarly, the Italian city of Milan charges 5€ per vehicle per day and the Norwegian capital Oslo recently adopted a toll of up to NOK 193 (∼20.34€) for vehicles above 3.5t during rush hours. Lastly, the third restriction banning trucks or certain kinds of vehicles can be often found in forms of weight, dimension or emission restrictions in real life. For example, the Hungarian capital Budapest has various limited traffic zones restricting the access for vehicles above, 3.5t, 7.5t or 12t. Similarly, we assume that vehicle access is regulated regarding the vehicle weight.

4.2 Agent Properties

Due to the heterogeneity of freight demand in urban areas, we implemented the possibility to set different receiver profiles. Inspired by the works of van Heeswijk et al. (2017), we modeled the following three receiver properties (i) average order volume, (ii) average order frequency, and (iii) number of supplying carriers. Table 2 shows the three receiver profiles and the corresponding percentages of receivers randomly assigned to each of it. Deviating from the receiver profiles in Table 2, as an aggregate of the total demand within each area an increased demand is set to each of the 20 receivers which are not within the UCC service area, so that the goods transported to the city center of Frankfurt amount on average to roughly 15% of the total amount of goods transported. Contrary to other works, we made the assumption that the UCC focuses primarily on palletized shipments due to parcel deliveries already being highly consolidated and adapted to urban policies by courier, parcel and express mail services (Ducret 2014). Based on reported values in literature, we set the weight range of pallets between 50 and 250kg (Agence de l'Environnement et de la Maîtrise de l'Energie 2004; van Duin et al. 2013).

Table 2: Summary of the receiver profiles.

Profile	Order moments/week	Orders/order moment	Pallets/order	Number of carriers	% of receivers
R1	1	1	1-3	1	20%
R2	1-2	1-2	1-2	4	40%
R3	2-3	1	1-2	6	40%

An important aspect to calculate the costs of deliveries are unloading times. There are several time estimates for the dwell times during unloading at the UCC and urban receivers. For example, Churchill (2014) reports turnaround times of 5 to 20 minutes for suppliers of the London Boroughs Consolidation Centre and Ruesch (2009) states average turnaround times of 12 minutes per vehicle for the London Heathrow Airport UCC. In line with Janjevic and Ndiaye (2017b), we assume 5 minutes for waiting and administrative tasks and 1.5 minutes per pallet unloaded at the UCC. Regarding the dwell times for unloading in urban areas, Allen et al. (2000) identify a number of operational key factors, such as the distance from the vehicle parking point to the unloading point, which influence the dwell times. By analyzing 24 studies from the UK between 1999 and 2008, Allen et al. (2008) show that the average dwell times vary between 8-34 minutes. Similarly to this, Schoemaker et al. (2006) report average stop durations ranging from 21 to 34 minutes for three Dutch cities. Following these findings, we set the range of dwell times per delivery stop between 8 and 34 minutes.

To calculate the volume-dependent handling costs of the UCC, a cost rate per unit or volume handled has to be set. Only few handling cost rates have been reported in the literature. For example, van Heeswijk et al. (2017) suggest that the price per m^3 of parcels varies with the total throughput of the UCC to account for economies of scale and estimate a range between 7 and 20 €/m^3. Simoni et al. (2018) assume in contrast much lower costs of 0.025 USD/ft^3 ($\sim$0.72€/m^3). Janjevic and Ndiaye (2017a) calculate transshipment costs of 0.58€/parcel resulting in 5.47€/m^3 for the stated average parcel volume of 0.106 m^3. Due to the lack of reliable data and based on the assumption that handling pallets should be cheaper than handling an equal volume of individual parcels, we estimate handling costs of 4€/pallet.

Besides the time spent on performing deliveries, the transport costs of the UCC and carriers strongly depend on the characteristics of the selected vehicles. Based on the works of Janjevic and Ndiaye (2017b) we selected cost parameters for two types of vehicles. Table 3 summarizes the vehicle properties obtained from literature differentiating between a medium-sized truck and a semi-trailer. Both the UCC and the carriers can choose the type of vehicles used during the heterogeneous vehicle routing problem and possess a sufficient number of vehicles to fulfill all daily transport requests and prevent back orders.

Table 3: Vehicle properties for carriers and UCC.

Vehicle property	Truck (7.49t)	Semi-trailer (39t)
Distance-based cost [€/km]	0.31	0.41
Time-based cost [€/h]	30.85	32.01
Pallet capacity [pal]	14	34
Weight capacity [kg]	3150	25000

4.3 Scenarios

For each scenario, we compare the usage of a UCC versus the case where each carrier delivers all of its shipments directly to the receivers. In the collaboration case using the UCC, each carrier delivers the urban shipments to the UCC and performs only the non-urban deliveries. The UCC, in turn, delivers the consolidated shipments to the urban receivers. Scenario 1 represents a situation where no urban access regulations are implemented. Scenario 2 represents a scenario with vehicle restrictions forbidding the usage of the larger vehicle within the UCC service area and delivery time windows from 8:00 until 11:00. Here we assume that receivers do not accept deliveries before 8:00, because the opening times of shops are usually after 8:00 in Frankfurt. Scenario 3 uses the same delivery time window but includes a zone-based access fee per day to enter the UCC service area instead of a restriction based on the vehicle size. Finally, scenario 4 shortens the delivery time window to 1.5 hours and in addition forbids the usage of large vehicles. Table 4 gives an overview of the studied scenarios.

Table 4: Studied scenarios.

Variable	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Delivery time window	–	8:00-11:00	8:00-11:00	8:00-9:30
Zone-based access fee	–	–	10€	–
Truck restrictions	–	<7.5t	–	<7.5t

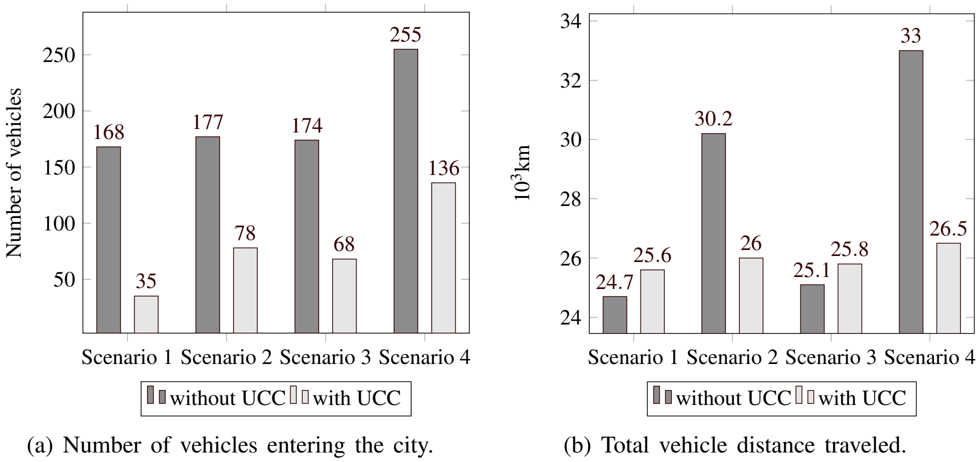
5 RESULTS

In this section, we present the results from the studied scenarios. Due to the lack of seasonal fluctuations in demand, each simulation run was performed for the period of one month, resulting in 27 days of operation simulated. For a better comparison, each scenario is evaluated using the same stochastic receiver demands. First, we study the cost-attractiveness of the UCC for each carrier under each scenario, considering the effect on the total operations of each carrier. Second, we briefly examine the number of vehicles entering the urban area and total vehicle kilometers per scenario. Table 5 shows that the cost-attractiveness to use the UCC varies among the carriers in each scenario. The average cost per pallet and receiver are stated for all deliveries, including deliveries outside the city of Frankfurt, which face no restrictions. The variation between the carriers can be explained by the different locations of each carrier shown in Figure 2 and detours to reach the UCC, but also by the stochastic order generation. As expected, it can be seen that more restrictive scenarios lead to a higher cost-attractiveness of the UCC. The comparison of scenarios 2 and 3 indicates that restricting the access for large vehicles has a bigger impact on the cost-attractiveness of the UCC than the implementation of zone-based access fees. In fact, the costs when using the UCC increase compared to scenario 2, while the costs when no UCC is used decrease in comparison to scenario 2. Thus, in scenario 3 the usage of the UCC results in higher costs for all carriers. In contrast, the results of scenario 2 indicate that the UCC is cost-attractive for two carriers. Scenario 4 shows the highest cost-attractiveness for all but one carrier and allows the assumption that the duration of delivery time windows has a high impact on the tour operations of the carriers and thus raises the cost-attractiveness of the UCC.

Table 5: Average cost per pallet and carrier with UCC and without UCC usage for each scenario.

	Scenario 1			Scenario 2			Scenario 3			Scenario 4		
Carrier	UCC	¬UCC	diff [%]	UCC	¬UCC	diff [%]	UCC	¬UCC	diff [%]	UCC	¬UCC	diff [%]
C1	9.67	9.16	-5.58	9.70	9.79	**0.87**	9.82	9.42	-4.19	9.75	10.01	**2.60**
C2	8.14	7.62	-6.77	8.18	7.97	-2.67	8.30	7.91	-4.92	8.24	8.35	**1.42**
C3	9.54	9.02	-5.77	9.57	9.72	**1.50**	9.66	9.39	-2.86	9.62	10.03	**4.10**
C4	8.62	8.13	-6.12	8.65	8.52	-1.54	8.75	8.38	-4.41	8.70	8.83	**1.40**
C5	7.64	7.28	-5.01	7.66	7.59	-1.06	7.75	7.49	-3.38	7.71	7.79	**0.99**
C6	7.95	7.32	-8.54	7.98	7.75	-3.04	8.12	7.58	-7.09	8.04	7.91	-1.60
C7	8.08	7.50	-7.79	8.11	7.88	-2.93	8.22	7.79	-5.52	8.17	8.28	**1.36**
C8	8.28	7.84	-5.64	8.31	8.24	-0.90	8.44	8.11	-4.05	8.37	8.57	**2.36**

The analysis of the total number of vehicles entering Frankfurt in Figure 3(a) shows that the usage of the UCC helps to reduce the number of vehicles entering the city enormously and that shorter delivery time windows increase the required number of vehicles for both the UCC and carriers. Our analyses of the total vehicle distance traveled in Figure 3(b) further shows that the usage of the UCC leads to more vehicle kilometers when no regulations are present, due to the resulting detours for the carriers. However, with the implementation of regulations, the total kilometers traveled increase more in the cases where no UCC is used than in the cases where the UCC is used.



(a) Number of vehicles entering the city.

(b) Total vehicle distance traveled.

Figure 3: Comparison of tour characteristics with and without the usage of the UCC for each scenario.

6 CONCLUSION

In this paper, we presented a simulation model using an actual road network and real retail locations to investigate the impact of urban access regulations on the cost-attractiveness of UCCs for carriers serving an entire region. Applied on a case study inspired by the Frankfurt Rhine-Main area, we showed that the implementation of urban access regulations offers potentials in raising the cost-attractiveness of UCCs. Especially shortened delivery time windows appear to have a large impact on carrier operations and thus increase the cost-attractiveness of using a UCC. However, the results also illustrated the difficulties to find scenarios where the UCC is beneficial for all carriers. Furthermore, the analyses show that with shortened delivery time windows and vehicle size restrictions the number of vehicles and distance traveled increases, due to the usage of smaller vehicles with less capacity. Thus, the restrictions can lead to additional negative effects caused by a larger number of smaller vehicles and increase in total kilometers traveled.

Conclusively, some limitations of this study and future areas of research can be identified. First, aspects, such as the UCC location and impacts of different receiver demand structures have not been studied in our simulation experiments and should be subject to further analyses and sensitivity analyses. In addition, cases with two or more UCCs could be investigated, especially for larger cities. Second, for future research, the study of more advanced cost-allocation methods such as the Shapley-Value or Nucleolus could be interesting to study. Third, longer time periods with seasonal demand changes could be studied and lastly, to find more viable situations for UCCs additional sources of income, such as value-added service and backhauling could be included into further studies as well.

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