Beta
Research School for Operations
Management and Logistics

An urban consolidation center in the city of Copenhagen: a simulation study

W.J.A. van Heeswijk, R. Larsen, A. Larsen

Beta Working Paper series 523

BETA publicatie	WP 523 (working paper)
ISBN	
ISSN	
NUR	
Eindhoven	February 2017

An urban consolidation center in the city of Copenhagen: a simulation study

Wouter van Heeswijk[a], Rune Larsen[b], and Allan Larsen[b]

[a]Department of Industrial Engineering and Business Information Systems, University of Twente

[b]Department of Management Engineering, Technical University of Denmark

February 24, 2017

Abstract

Urban consolidation centers (UCCs) have a key role in many initiatives in urban logistics, yet few of them are successful in the long run. The high costs have proven a barrier that prevents attracting a sufficiently high number of UCC users. In this paper, we study how the user base of a UCC develops under a variety of administrative policies. We perform an agent-based simulation applied to the city of Copenhagen, making use of its real street network and retailer locations. We collect data from a variety of sources to help modeling the agents. Both the data and case setup are validated by means of expert interviews. We test 1,458 schemes that combine several administrative measures and cost settings. The numerical results indicate that most schemes yield significant environmental benefits; many of them are able to reduce the truck kilometers driven by about 65% and emissions by about 70%. The key challenge is to identify schemes that are also financially sustainable. We show that it is essential for the UCC to ensure the commitment of carriers as soon as possible, as the bulk of the revenue can be generated from this target group. Subsequent revenues may be generated by offering value-adding services to receivers. Based on the numerical experiments, we pose various propositions that aid in providing favorable conditions for a UCC, improving its chances of long-term success.

1 Introduction

Urban populations are growing rapidly; a projection by the United Nations estimates that in the year 2050, an additional 2.5 billion people will be living in urban areas; by then, the share of the world population living in urban areas is expected to equal 66% (United Nations 2014). As many urban residents consume goods sold by local retailers, the demand for goods in urban areas is growing fast as well. In turn, this causes an increase in the volumes of urban freight transport (Transmodal 2012). In addition, just-in-time principles gain popularity among retailers, meaning that they hold low volumes in storage, order small volumes, and order more frequently (Crainic et al. 2004, Dablanc 2011). Furthermore, retailers nowadays have higher demands with respect to service levels, imposing more narrow delivery windows and expecting faster delivery. As a result of these developments, freight flows are becoming increasingly fragmented, making it difficult for carriers to plan efficient routes. This is particularly the case for small freight carriers, which comprise about 85% of the transport market (Dablanc 2011). Finally, the rise of e-commerce plays a major role in reshaping the landscape of urban freight transport.

The surge in the number of freight transport movements has a hazardous impact on life expectancy and on the quality of life in urban areas, as well as on the environment. Although freight transport comprises about 15% of the total traffic flows in cities, it causes up to 50% of traffic emissions (Dablanc 2011). Furthermore, large trucks disproportionally contribute to external costs such as noise hindrance, road congestion, and traffic safety. Another concern – especially relevant for many European cities – is that historic city centers with narrow streets are unfit to facilitate large-scale freight transport (Ambrosino et al. 2007). The consequences are heavily congested streets and shopping areas, as well as damage inflicted by heavy trucks upon monumental properties.

The imminent need to improve the efficiency and to reduce the environmental impact of urban freight transport is recognized by both companies and local governments. Many initiatives have been considered to this end. Urban consolidation centers (UCCs) have a central role in many solution concepts to reduce the impact of urban freight transport (Quak 2008, Transmodal 2012). The presence of a UCC allows trucks to unload at the edge of the urban area, rather than entering the city center themselves to deliver goods. The underlying idea is that bundling freight at the UCC results in a more efficient last-mile distribution, while simultaneously allowing to dispatch cleaner and smaller vehicles within the urban area. Despite the theoretical benefits, the vast majority of UCCs have failed in practice (Browne et al. 2005). The extra costs introduced in the supply chain have proven to be a major barrier to overcome. UCCs are often not able to attract sufficient users – with users being receivers and carriers – to reach their break-even point. Furthermore, UCCs often heavily rely on subsidies, leading to unsustainable operations when subsidies are halted.

In an overview study of both former and active UCC initiatives, Browne et al. (2005) indicate that the most successful schemes combine company-driven initiatives with government policies. The commitment of companies is essential, yet supportive regulation and subsidies are typically required as well for sustainable implementations. Despite a handful of successful UCCs being in existence, our knowledge regarding sustainable business models remains limited (Allen et al. 2012). In this paper, we perform a simulation study to increase insight into the success factors of a UCC. We take the city of Copenhagen, Denmark as a test case, using real data for the UCC location, retailer locations, and the street network. To accurately represent the actors involved in the urban supply chain, we collect data from various studies. Our test case is validated by means of expert interviews. With respect to the tested policies we take a somewhat liberal approach; some measures might not be legally feasible under the current Danish legislation. Nevertheless, testing such measures yields useful insights, as our findings are particularly relevant when there is the political will to combat the hazardous effects of urban freight transport.

The remainder of the paper is structured as follows. In Section 2, we provide a literature review. We proceed to discuss the proposed methodology in Section 3. The experimental setup is described in Section 4. Section 5 presents and discusses the results of the simulation experiments. Finally, we present the main conclusions in Section 6.

2 Literature Review

A UCC is a logistics facility that is located in the proximity of an urban area (Browne et al. 2005). The service area of a UCC may be a shopping area, a city center, or a larger urban region. The UCC allows for the transshipment of freight, enabling carriers to outsource their last-mile distribution. As the UCC is able to bundle freights from multiple carriers, it may perform the last-mile delivery more efficiently than the carriers could themselves (Huschebeck and Allen 2004, Quak and de Koster 2009). In addition, the UCC can dispatch vehicles that are tailored to last-mile delivery, such as electric delivery vans. Hence, an additional reduction in environmental impact could be achieved. The potential benefits are highest when considering freight flows that are inefficiently organized (Browne et al. 2005, Van Rooijen and Quak 2010). It is important to note that transport might be organized efficiently from the perspective of the carrier, but not from the perspective of the city, e.g., a truck may visit multiple cities during the same route (Verlinde et al. 2012).

On a high level, two business models for UCCs can be distinguished (Van Rooijen and Quak 2010). In the first one, it is the carrier that outsources the deliveries in the city to the UCC. The costs for last-mile distribution are disproportionally high for carriers, as travel speeds are low and unloading at the receivers is time-consuming. Restrictive local regulations may be additional reasons for carriers to outsource delivery to the UCC. Despite these incentives to use the UCC, the price of outsourcing is often too high for carriers (Van Rooijen and Quak 2010, Kin et al. 2016). In the second business model, the receiver in the urban area selects the UCC as its delivery address. The UCC can bundle goods stemming from multiple origins into a single delivery, such that the receiver spends less time on receiving goods and thus can dedicate less personnel hours to this non-core task. However, as the shipping costs are generally embedded in the order price, paying the UCC to perform last-mile deliveries introduces additional costs. The efficiency gains obtained by bundling are unlikely to compensate for these costs (Verlinde et al. 2012). For the retailer, the key merits of the UCC are the value-adding services it offers. Van Rooijen and Quak (2010) and Allen et al. (2012) describe various value-adding services. First, temporary storage at the UCC allows retailers to hold goods in a nearby position, without having to dedicate valuable shop floor space. Second, waste collection (e.g., cardboard waste) can be performed by the UCC; this service is typically not offered by carriers, as they focus on forward logistics. Third, the UCC can collect goods that the retailer has sold online (e-tailing). From the UCC onwards, these goods are transported by an external carrier; due to the larger volumes handled, the UCC may negotiate lower transport rates than the individual retailers could. Fourth, home deliveries in the same city can also be performed by the UCC, being responsible for both collection and delivery. Finally, the UCC can also offer specialized services tailored to the needs of individual retailers, such as splitting pallets into smaller loads, or putting clothes on hangers and labeling them before delivery to a fashion retailer.

In an elaborate review, Browne et al. (2005) analyze 67 UCC schemes, considering operational schemes, trials, and feasibility studies. They report that the vast majority of UCCs is unable to survive in the long term. For example, out of 200 known operational schemes in Germany, only 15 were still active at the time of the study (Browne et al. 2005). The main reasons for failure are (i) the high costs of the extra transshipment and (ii) a lack of added value from the perspective of both carriers and receivers (Browne et al. 2005, Van Duin et al. 2010, Verlinde et al. 2012). As a result, UCCs are often unable to generate a sufficiently high throughput to reach the break-even level that is required for a sustainable business model. The inability to attract sufficient users is partially caused by a lack of external support. In the start-up phase of a UCC, local administrators often provide subsidies. When this financial support is ended, the UCC is generally unable to survive (Browne et al. 2005, Kin et al. 2016).

As the low success rate of UCCs might suggest, little analysis has been performed on their long-term success factors (Van Rooijen and Quak 2010). First of all, there is often an absence of a clearly defined target group of potential UCC users. Many logistics streams are already efficiently organized, and a transshipment may actually make them less efficient (Van Rooijen and Quak 2010). A second challenge is that retailers, carriers, and administrators may all benefit in some way from a UCC, yet strive to accomplish divergent objectives (Bektaş et al. 2015). In particular, the objective to reduce environmental costs is typically difficult to combine with cost efficiency for the actors involved. Therefore, system-wide optimization often does not generate solutions to which autonomous actors would commit in practice. Taniguchi et al. (2014) state that agent-based simulation is the most applicable method to study the behavior of and interaction between the various agents in the complex environment of urban logistics. Although agent-based simulation lacks the refinement to analyze detailed interactions (Bektaş et al. 2015), it is a suitable tool to obtain generic insights into the behavior of a system under varying circumstances. In recent years, various efforts have been made to evaluate urban logistics schemes using agent-based models. Tamagawa et al. (2010) evaluate the effects of road pricing and truck bans, using a learning model to reflect agents' decision making under evolving circumstances. Van Duin et al. (2012) address the financial model and environmental impact of UCCs. They study various settings for UCC service fees, road pricing, and subsidies. Wangapisit et al. (2014) research the use of UCCs when introducing parking constraints, while simultaneously providing subsidies to carriers. Finally, Van Heeswijk et al. (2016) study various schemes in which they combine the role of a UCC, carrier coalitions, and government interventions. A common characteristic of these agent-based simulation studies is that they consider relatively small and simplified networks. Furthermore, they do typically not model the agents in accordance with data obtained from practice. Therefore, it is not clear to what extent their findings translate to more realistic settings.

We conclude this section with the literature gaps that we address with this paper. The first contribution of this study is the identification of sustainable business models for UCCs. Although several studies have been performed on the subject, they ultimately offer few insights into good practices for UCCs and how administrative policies may be deployed to elevate the chances of success for a UCC. By performing experiments on a realistic test network and testing over 1400 combinations of measures, this study provides new insights into these matters. Our second contribution is the construction of agent profiles based on real data. By modeling agents in accordance with data obtained from practice and by validation via expert interviews, we aim to model urban supply chains in a more representative manner than in existing agent-based simulation studies.

3 Methodology

To evaluate a variety of urban logistics schemes, we make use of the agent-based simulation framework of Van Heeswijk et al. (2016). As stated in the previous section, agent-based simulation enables to evaluate the behavior of autonomous agents in complex environments, and is therefore a suitable tool to analyze urban logistics schemes. The objective of our simulation study is to identify urban logistics schemes that (i) reduce the environmental impact of freight transport in the city center, (ii) are based on a financially sustainable business model, and (iii) incentivize commitment of the actors involved. The agent types included in the framework are receivers, carriers, the UCC, and the local administrator. To reflect the divergent goals of these agents, every agent pursues its own objectives within the constraints of the system.

At the heart of the framework is a discrete-event simulation over a finite decision horizon, with $\mathcal{T} = \{0, 1, \ldots, T\}$ representing the set of decision epochs. The decision epochs are separated by equidistant time intervals that each represent one day. We distinguish between three levels of decision making (strategic, tactical, and operational); we discuss the different levels of decision making in more detail in Section 3.2. Strategic decisions are fixed at the start of each simulation run, i.e., at $t = 0$. Tactical decisions can only be made at a limited set of decision epochs $\mathcal{T}^{tac} \subset \mathcal{T}$ – for this study we set the interval between adjacent tactical decision epochs equal to two months – and represent a commitment for a time period of medium length. Thus, decisions made at a given tactical decision epoch are fixed until the subsequent tactical decision epoch. Finally, orders (i.e., goods demanded by the receivers) are randomly generated at every decision epoch $t \in \mathcal{T}$, upon which all agents make their operational decisions. In Section 3.3, we describe the cost functions and KPIs of the agents.

We denote the set of receivers by $\mathcal{R}$, the set of carriers by $\mathcal{C}$, and the UCC by h. To individual agents we refer as $r \in \mathcal{R}$ and $c \in \mathcal{C}$, respectively. The city of Copenhagen is represented by the graph $\mathcal{G} = \{\mathcal{V}, \mathcal{A}\}$, with the vertex set $\mathcal{V}$ containing both the UCC location and the retailer locations, and the arc set $\mathcal{A}$ connecting the vertices. The travel time between any pair of vertices is obtained with OpenStreetMap (OSM Foundation 2017).

In our model, we make a number of key assumptions. We assume that (i) all orders that are generated at a given decision epoch are delivered before the subsequent decision epoch, (ii) all agents update their tactical decisions at the same decision epochs, (iii) order frequencies and order volumes of receivers cannot be influenced during the simulation, (iv) receivers and carriers make their decisions whether to join the UCC independent of each other, and (v) UCC prices and -costs decrease when the amount of volume that is handled by the UCC increases. Assumptions (i) and (ii) are made for the sake of computational speed, (iii) is based on the notion that receivers are subject to inventory constraints and the demand of consumers, (iv) reflects an absence of cooperation efforts and a lack of knowledge regarding the actions of competitors, and (v) implies that economies of scale improve the efficiency of the UCC.

3.1 Outline of the simulation framework

In this section, we describe the general outline of the simulation framework. We start by introducing the notation required to define the problem state. Let $l \in \mathcal{L} = \{\frac{1}{y}, \ldots, 1\}$ be the volume of an order, with $y \in \mathbb{N}$. The element l represents volume in terms of the vehicle capacity of the smallest vehicle type that is defined in the simulation, such that $l = 1$ equals a full truckload of this vehicle type. It follows that every order can be transported by any vehicle. A unique combination of carrier, receiver, and volume represents the order type (c, r, l). The number of orders of a given order type is denoted by $I_{t,c,r,l} \in \mathbb{N}$. Now, let $I_t = (I_{t,c,r,l})_{\forall (c,r,l) \in \mathcal{C} \times \mathcal{R} \times \mathcal{L}}$ be a vector that provides the number of orders per order type demanded at time t. All orders placed at decision epoch t are delivered before $t+1$, e.g., within one day. Every combination of numbers per order type demanded represents a unique order arrival; let Ω_t be the set of all possible order arrivals at decision epoch t. We represent arrivals of new orders with the variable $\omega_t = (\tilde{I}_{t,c,r,l})_{\forall(c,r,l)\in\mathcal{C}\times\mathcal{R}\times\mathcal{L}}$, with $\omega_t \in \Omega_t$. The order demand of receivers is generated according to the random variable W_t, with ω_t representing a simulated realization of W_t. As all orders in the system at t are delivered before the next decision epoch $t+1$, orders from previous decision epochs have no impact on the system. Thus, at every decision epoch $t \in \mathcal{T}$, we update the orders in the system as follows:

$$I_{t,c,r,l} = \tilde{I}_{t,c,r,l} \qquad \forall(c,r,l) \in \mathcal{C}\times\mathcal{R}\times\mathcal{L} \ , \tag{1}$$

Based on the order arrivals, both the UCC and the carriers decide on their delivery routes. To determine which orders should be shipped via the UCC, we keep track of the agents that have committed themselves to use the UCC. If a carrier or receiver commits to the UCC, this means that all its shipments are handled by the UCC. The binary variable $\gamma^{rec,tr}_{t,r} \in \{0,1\}$ represents whether receiver r makes use of the base service of the UCC (i.e., bundled deliveries) at time t; the vector $\gamma^{rec,tr}_t = (\gamma^{rec,tr}_{t,r})_{\forall r\in\mathcal{R}}$ stores this information for all receivers. The variable $\gamma^{rec,val}_{t,r} \in \{0,1\}$ and the vector $\gamma^{rec,val}_t = (\gamma^{rec,val}_{t,r})_{\forall r\in\mathcal{R}}$ have a similar purpose, but instead describe whether the receiver outsources its value-adding services to the UCC. For a receiver to outsource its value-adding services, it must be pay the fee for the base service as well, i.e., $\gamma^{rec,val}_{t,r}$ can have a value of 1 if and only if $\gamma^{rec,tr}_{t,r} = 1$. Finally, the variable $\gamma^{car}_{t,c} \in \{0,1\}$ and the corresponding vector $\gamma^{car}_t = (\gamma^{car}_{t,c})_{\forall c\in\mathcal{C}}$ describe whether the carrier outsources its last-mile transport to the UCC.

To reflect economies of scale that may be achieved by the UCC, various price- and cost functions of the UCC are updated based on the ratio between the volume that passes through the UCC and the total volume that enters the city. We discuss this updating procedure in Section 3.2; for our definition of the problem state it suffices to introduce the notation for the volume ratio. This ratio is required for the tactical decisions of the UCC, and is therefore an element of the state. Let $l^{ucc}_{t',t''} \in [0,1]$ – with $t',t'' \in \mathcal{T}^{tac}$ and $t' < t''$ – be the volume handled by the UCC in the period between the most recent tactical decision epoch t'' and the second most-recent tactical decision epoch t', divided by the total order volume entering the city during the same time period.

We have now introduced all elements necessary to define the problem state. The problem state is comprised of five elements: the vector of orders I_t, the vector of receivers that use the base transport service of the UCC $\gamma^{rec,tr}_t = (\gamma^{rec,tr}_{t,r})_{\forall r\in\mathcal{R}}$, the vector of receivers that outsource their value-adding services to the UCC $\gamma^{rec,val}_t = (\gamma^{rec,val}_{t,r})_{\forall r\in\mathcal{R}}$, the vector of carriers that use the UCC $\gamma^{car}_t = (\gamma^{car}_{t,c})_{\forall c\in\mathcal{C}}$, and the volume ratio $l^{ucc}_{t',t''}$. We denote the problem state at time t as

$$S_t = (I_t, \gamma^{rec,tr}_t, \gamma^{rec,val}_t, \gamma^{car}_t, l^{ucc}_{t',t''}) \ . \tag{2}$$

3.2 Agent intelligence

In this subsection, we describe the agent intelligence embedded in the simulation model. Small and independent actors will typically not use state-of-the-art algorithms; we reflect this practice by representing the decision processes of actors with relatively simple heuristics. As explained in the previous section, we distinguish between decisions made on the strategic, tactical and operational level, which we separately discuss here. Figure 1 provides a flowchart of the simulation model, describing the sequence of the decisions that are made by the various agent types.

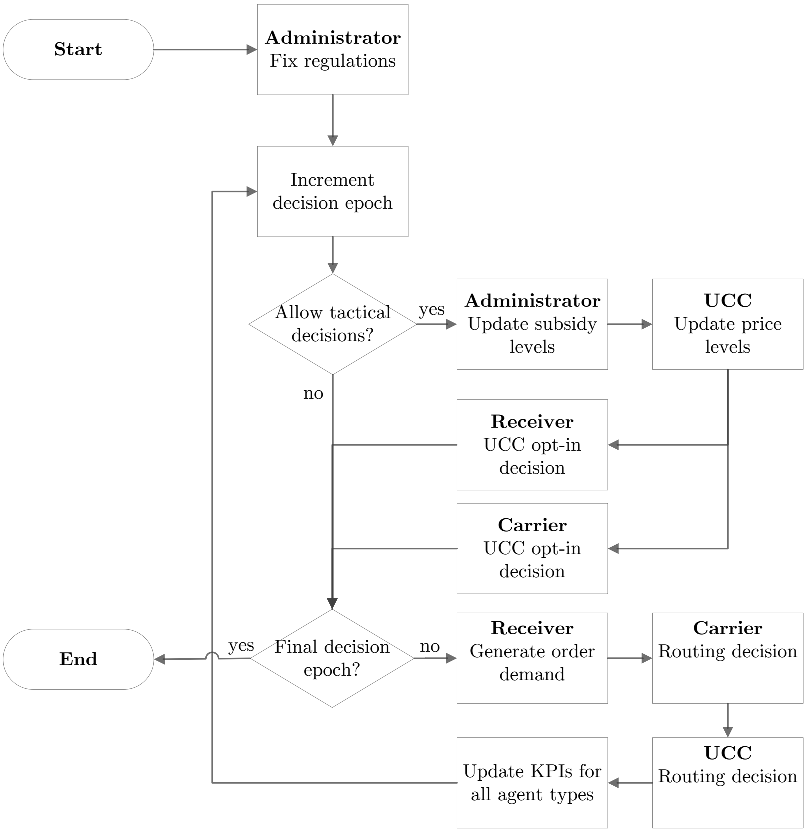

Figure 1: *Flowchart of the simulation model.*

In our simulation, strategic decisions are made only by the administrator. These long-term decisions are fixed at $t = 0$ and involve deciding on the subsidy levels, setting the length of the subsidy period, determining the accessibility measures to the city, and setting the policy costs. In this simulation model, we test one accessibility measure, namely an access time window; large trucks may only drive in the environmental zone within this window. Furthermore, we set one cost measure, which is the zone access fees, i.e., a fixed fee per large truck entering the environmental zone of the city. As the UCC uses small trucks, it is exempt from both measures.

The tactical decisions are made at the decision epochs $t \in \mathcal{T}^{tac}$; these decisions are made sequentially by the administrator, the UCC, and then (in parallel) by the receivers and carriers. First, the administrator may alter its subsidy levels. Subsidy levels are expressed as a percentage of the price charged by the UCC and function as a discount on the prices charged to the carriers and receivers. For example, when the carrier receives a 20% subsidy, this reduces the price it must pay to the UCC by 20%. Subsidies allocated to the UCC itself are reflected as a discount in the prices charged to both the receivers and the carriers. Furthermore, when the administrator allocates subsidies to multiple agent types, their effect is cumulative, e.g., when both the UCC and the carriers are subsidized for

20%, the price reduction is 40% for the carriers and 20% for the receivers. The subsidy percentages are fixed at the start of the simulation, and are always set to 0% after the subsidy period has ended.

The second tactical decision involves altering the cost- and price levels of the UCC. We adjust these levels based on the volume ratio $l_{t',t''}$, which has been defined in Section 3.1. By varying the costs and prices for the UCC based on the volume it handles, we reflect economies of scale that are achieved by handling larger volumes. Here we focus on the updating procedures; the cost- and price variables (or functions) themselves are explained in more detail in Section 3.3. At each tactical decision epoch, we update three price variables and two cost variables:

$P_t^{ucc,car,tr}$	Price charged to the carrier for outsourcing its last-mile distribution, a fixed fee per outsourced delivery stop that is identical for each carrier;
$P_t^{ucc,rec,tr}$	Fixed fee for the base service of bundled deliveries as charged to the receiver, identical for each receiver;
$P_t^{ucc,val}$	Receiver-dependent fee for performing value-adding services;
$C_t^{ucc,hd}$	Volume-based costs for handling goods at the UCC;
$C_t^{ucc,val}$	Receiver-specific cost to perform value-adding services.

For each of the aforementioned cost- and price variables, we define a range that contains the values that the variable may take. We express the volume handled by the UCC as the ratio of the total volume that enters the city (i.e., the cumulative volume of the target group). A ratio of 0 corresponds to the highest cost- and price levels, a ratio of 1 corresponds to the lowest levels. Within the ranges, we assume a linear relation between costs/prices and the volume ratio. We provide an example of the updating procedure for the price variable $P_t^{ucc,rec,tr}$; the other cost and price variables are updated in a similar manner. Let $\bar{P}^{ucc,rec,tr}$ be the upper price bound and $\underline{P}^{ucc,rec,tr}$ be the lower price bound. The volume ratio $l_{t',t''}$ determines the price level within this range. We update receiver prices as follows:

$$P_t^{ucc,rec,tr} = (1 - l_{t',t''}) \cdot \bar{P}^{ucc,rec,tr} + l_{t',t''} \cdot \underline{P}^{ucc,rec,tr} \quad .$$

After adjusting the subsidies, cost levels, and price levels, the receivers and carriers independently and in parallel decide whether or not to commit to the UCC. For any agent that chooses to use the UCC, the UCC becomes responsible for the last-mile distribution of all the agent's goods, until at least the next tactical decision epoch. The decision to opt-in or opt-out is based on the expected future costs of both options, given the updated subsidy levels and assuming that the agent unilaterally changes its decision. To compute the expected future costs at a given tactical decision epoch, we first generate N sample paths of order arrivals that stretch τ^{sample} decision epochs into the future, with $n \in \{1, \dots, N\}$ being the index for the sample path and $t_n \in \{1, \dots, \tau^{sample}\}$ being the time index for the sample states of path n. For every $n \in \{1, \dots, N\}$, we obtain a set of sample states $\{\tilde{S}_{t+1_n}, \dots, \tilde{S}_{t+\tau_n^{sample}}\}$.

In each sample state $\tilde{S}_{t+t_n}$, we keep all but one binary variable at the same level as in S_t, i.e., for each agent we base our forecasts on the UCC commitments as they are before the update. We introduce the help variables $\tilde{\gamma}_r^{rec,tr} \in \{0,1\}$, $\tilde{\gamma}_r^{rec,val} \in \{0,1\}$, and $\tilde{\gamma}_c^{car} \in \{0,1\}$. Adjusting the value of these variables allows us to compute cost forecasts for both the case in which it uses the UCC and the case in which it does not commit to the UCC. Based on the generated sample states, we compute the expected costs with the cost functions $\tilde{C}^{rec}(\tilde{S}_{t+t_n}, \tilde{\gamma}_r^{rec,tr}, \tilde{\gamma}_r^{rec,val})$ and $\tilde{C}^{car}(\tilde{S}_{t+t_n}, \tilde{\gamma}_c^{car})$; these functions are similar to the functions that we define in Section 3.3. Computing the costs for the sets of sample states yields the expected future costs for both the case in which the agent unilaterally decides to use the UCC and the case in which the agent opts for direct transport. Minimizing the expected future costs yields the updated tactical decision. Equation (3) shows how we update the tactical decision for the receivers, Equation (4) shows the same for the carriers.

$$[\gamma_{t,r}^{rec,tr}, \gamma_{t,r}^{rec,val}] = \underset{\substack{\tilde{\gamma}_r^{rec,tr} \in \{0,1\}, \\ \tilde{\gamma}_r^{rec,val} \in \{0,1\}}}{\arg\min} \frac{1}{N} \sum_{n=1}^{N} \sum_{t_n=1}^{\tau^{sample}} \tilde{C}^{rec}(\tilde{S}_{t+t_n}, \tilde{\gamma}_r^{rec,tr}, \tilde{\gamma}_r^{rec,val}) \qquad \forall r \in \mathcal{R} \ , \tag{3}$$

$$\gamma_{t,c}^{car} = \underset{\tilde{\gamma}_c^{car} \in \{0,1\}}{\arg\min} \frac{1}{N} \sum_{n=1}^{N} \sum_{t_n=1}^{\tau^{sample}} \tilde{C}^{car}(\tilde{S}_{t+t_n}, \tilde{\gamma}_c^{car}) \qquad \forall c \in \mathcal{C} \ . \tag{4}$$

We now discuss the operational decisions of the simulation model, which are made at every decision epoch $t \in \mathcal{T}$. Based on the realization of the random variable W_t – which translates into receivers placing orders – shipments are assigned to carriers. Both carriers and the UCC make routing decisions for the last-mile distribution. We use the Clarke-Wright savings algorithm to construct routes, followed by a 2-opt improvement heuristic. Such an approach is similar to the routing algorithms that are often applied in practice (Quak and de Koster 2009). We represent the resulting routes as follows. Let $\mathcal{Q}^{ucc}$ be the set of vehicles operated by the UCC, with $q \in \mathcal{Q}^{ucc}$ referring to an individual vehicle. The vehicle notation for carriers is similar. The delivery route of vehicle q within the city is an ordered set of arcs, denoted by $\delta_{t,q}^{ucc}$ ($\delta_{t,c,q}^{car}$ for carriers). When generating routes, we take into account the capacity of the vehicle and possible access time restrictions. To satisfy these restrictions, an agent may need to dispatch multiple vehicles at a single decision epoch, which results in multiple routes being executed by a single agent; sets of routes are denoted by Δ_t^{ucc} and $\Delta_{t,c}^{car}$ respectively. Finally, we use $\Delta_t = \Delta_t^{ucc} \cup \bigcup_{c \in \mathcal{C}} \Delta_{t,c}^{car}$ to denote the set of all routes executed at t.

3.3 Cost functions and KPIs

To quantify the results of the study, we monitor both environmental performance and financial performance. We measure environmental performance by three sets of indicators. First, we measure global emissions (CO_2). These emissions have a negative environmental impact, yet their effects are not restricted to the city boundaries. Second, we measure local emissions (SO_2, NO_x, $PM_{2.5}$); these emissions directly affect health and environment in urban areas. Third, we measure two vehicle-related performance indicators, namely the number of vehicles in the urban area (itemized per vehicle type) and the distance covered per vehicle type. These indicators serve as a proxy for external costs that cannot be accurately measured in our simulation model, such as noise hindrance, traffic safety, and influence on congestion.

The four different agent types, along with their objectives, constraints and KPIs, are listed in Table 1. We now proceed to formalize the cost functions of the agents. We only introduce the notation required for a general understanding of the framework; for a more detailed representation we refer to Van Heeswijk et al. (2016).

Table 1: *Overview of the agent types in the simulation framework*

Agent type	**Objective**	**Constraints**	**KPIs**
Carrier	Minimize costs	Local regulations	Costs transport Costs outsourcing last-mile distribution Costs administrative policies
Receiver	Minimize costs	Local regulations	Costs receiving Costs outsourcing last-mile distribution Costs value-adding services (in-house) Costs value-adding services (outsourced)
UCC	Maximize profit	Local regulations	Income last-mile distribution Income value-adding services Costs transport Costs value-adding services
Administrator	Minimize environmental costs	Profitability of the agents Functioning supply system	$\mathrm{CO_2}$ (global emissions) $\mathrm{SO_2}$, $\mathrm{NO_x}$, $\mathrm{PM_{2.5}}$ (local emissions) Number of vehicles (per type) Total vehicle distance (per type) Income administrative policies Costs subsidies

We start by defining the cost function for the carriers. To distinguish between routes that visit all delivery addresses and routes that only visit the UCC, we again use the help variable $\tilde{\gamma}_c^{car}$. Let $\Delta_{t,c}^{car}|\tilde{\gamma}_c^{car}=0$ be the route set corresponding to the case in which the carrier visits all its delivery addresses (possibly including the UCC) itself, and let $\Delta_{t,c}^{car}|\tilde{\gamma}_c^{car}=1$ correspond to the case in which the carrier only visits the UCC. The function $C^{car,tr}(\cdot)$ returns the transport costs for a given route set, including the unloading costs at the receivers. With $C^{car,tr}(\Delta_{t,c}^{car}|\tilde{\gamma}_c^{car}=0)$ we obtain the transport cost that correspond to the carrier visiting all its delivery addresses itself; $C^{car,tr}(\Delta_{t,c}^{car}|\tilde{\gamma}_c^{car}=1)$ yields the transport costs if the carrier only visits the UCC. If the carrier outsources its last-mile distribution, the only destination of the route is the UCC. The information embedded in the route set suffices to compute the total travel time, the number of receivers visited, and the zone access fees paid. If the carrier outsources its last-mile distribution, a fixed amount per stop must be paid to the UCC. These costs are represented by $P_t^{ucc,car,tr}(\Delta_{t,c}^{car}|\tilde{\gamma}_c^{car}=0)$ – the route notation contains the number of stops that are outsourced – and depend on the price charged by the UCC at time t. Finally, $P_t^{car,ucc,sb}(\Delta_{t,c}^{car}|\tilde{\gamma}_c^{car}=0)$ denotes the subsidy that the carrier receives when using the UCC, which is a fixed percentage of the price per stop it pays to the UCC. The cost function of carrier $c\in\mathcal{C}$ at time t is given by

$$C_t^{car}(\gamma_{t,c}^{car},\Delta_{t,c}^{car}|\tilde{\gamma}_c^{car}=0,\Delta_{t,c}^{car}|\tilde{\gamma}_c^{car}=1)=(1-\gamma_{t,c}^{car})C^{car,tr}(\Delta_{t,c}^{car}|\tilde{\gamma}_c^{car}=0)+$$
$$\gamma_{t,c}^{car}C^{car,tr}(\Delta_{t,c}^{car}|\tilde{\gamma}_c^{car}=1)+\gamma_{t,c}^{car}P_t^{ucc,car,tr}(\Delta_{t,c}^{car}|\tilde{\gamma}_c^{car}=0)-\gamma_{t,c}^{car}P_t^{car,ucc,sb}(\Delta_{t,c}^{car}|\tilde{\gamma}_c^{car}=0)\ .$$

The costs incurred by the receiver are comprised of the following five elements: (i) the receiving costs $C^{rec,rc}\left(r,\Delta_t^{ucc},\bigcup_{c\in\mathcal{C}}\Delta_{t,c}^{car}\right)$, which depend on the number of vehicles that visit its premises and – in case of visiting carrier trucks only – whether shifted access windows are imposed, (ii) the receiver-specific costs for performing value-adding services in-house $C^{rec,val}(r)$, (iii) the costs for outsourcing last-mile transport to the UCC $P_t^{ucc,rec,tr}$ (i.e., the base service of bundled deliveries, for which the UCC charges the same fixed fee to every receiver), (iv) the receiver-specific costs for outsourcing value-adding services to the UCC $P_t^{ucc,val}(r)$, and (v) the subsidy income when using the UCC $P_t^{rec,ucc,sb}$, which is a fixed percentage of the price that is paid to the UCC for the base service. The cost function of receiver $r \in \mathcal{R}$ at time t is

$$\begin{aligned} C_t^{rec}(r, \gamma_{t,r}^{rec,tr}, \gamma_{t,r}^{rec,val}, \Delta_t) = C^{rec,rc}\left(r, \Delta_t^{ucc}, \bigcup_{c\in\mathcal{C}} \Delta_{t,c}^{car}\right) + (1-\gamma_{t,r}^{rec,val})C^{rec,val}(r) \\ +\gamma_{t,r}^{rec,tr}P_t^{ucc,rec,tr} + \gamma_{t,r}^{rec,val}P_t^{ucc,val}(r) - \gamma_{t,r}^{rec,tr}P_t^{rec,ucc,sb} \quad . \end{aligned}$$

For the UCC, transport costs are calculated similarly to those of the carriers and are denoted by $C^{ucc,tr}\left(\Delta_t^{ucc}\right)$. The remainder of the costs and prices of the UCC are time-varying. The handling costs of incoming orders for the UCC are denoted by $C_t^{ucc,hd}(\bigcup_{c\in\mathcal{C}} \Delta_{t,c}^{car})$ and the costs for performing value-adding services are given by $C_t^{ucc,val}(r)$. The prices charged by the UCC are the price charged per outsourced stop to the carrier $P_t^{ucc,car,tr}(\Delta_{t,c}^{car}|\tilde{\gamma}_c^{car}=0)$, the price for the base service charged to the receiver $P_t^{ucc,rec,tr}$, and the price to perform the value-adding services for a receiver $P_t^{ucc,val}(r)$. Finally, the UCC may receive a subsidy $P_t^{ucc,sb}$, which is a percentage of the total prices charged to the carriers and the receivers (only for the base service, not the value-adding services). The cost function of the UCC is as follows:

$$\begin{aligned} C_t^{ucc}(\gamma_t^{rec,tr}, \gamma_t^{rec,val}, \gamma_t^{car}, \Delta_t) = C^{ucc,tr}\left(\Delta_t^{ucc}\right) + C_t^{ucc,hd}\left(\bigcup_{c\in\mathcal{C}} \Delta_{t,c}^{car}\right) + \\ \sum_{r=1}^{|\mathcal{R}|}\gamma_{t,r}^{rec,val}C_t^{ucc,val}(r) - \sum_{c=1}^{|\mathcal{C}|}\gamma_{t,c}^{car}P_t^{ucc,car,tr}(\Delta_{t,c}^{car}|\tilde{\gamma}_c^{car}=0) - \sum_{r=1}^{|\mathcal{R}|}\gamma_{t,r}^{rec,tr}P_t^{ucc,rec,tr} - \\ \sum_{r=1}^{|\mathcal{R}|}\gamma_{t,r}^{rec,val}P_t^{ucc,val}(r) - P_t^{ucc,sb} \quad . \end{aligned}$$

The final agent type is the administrator. For this agent, we do not define an explicit cost function; this would require either monetizing the environmental costs or assigning weights to the different objectives. Instead, from the simulation output we interpret how the administrator performs on its various KPIs. Although we monitor the financial performance of the administrator – as we want to allocate subsidies as efficiently as possible – we assume that cost minimization is not a target in itself. Instead, financial expenses are a means to improve the environmental performance.

4 Experimental setup

In this section, we describe the setup of the simulation study. The goal of the study is to identify schemes that significantly reduce the environmental impact of freight transport by using the UCC. As high costs are the main barrier for a starting UCC, we consider the use of subsidies and regulations to encourage the use of the UCC in the startup phase. To this end, we test a variety of measures to support the UCC. We enforce that subsidies are only temporary; after two years the UCC must be able to operate independently. This implies that the UCC has limited time to create a sufficiently large user base. The UCC should reach a critical mass such that the operational costs are low enough to be able to offer competitive prices to its users. Each simulation runs represents a period of five years; the performance in the last two years is used to evaluate whether the UCC achieves the desired performance.

Of particular interest is the sequence in which users are attracted. If the receiver selects the UCC, the carrier supplying this receiver essentially outsources its last-mile distribution without costs. From this perspective, it is sensible to first generate commitment from the carriers, as this leaves open the opportunity for receivers to pay for value-adding services. Receivers, on the other hand, may be easier to convince to use the UCC, as their perceived benefits (including value-adding services) are usually greater than for the carrier. We test a variety of subsidy allocations to observe how they affects the sequence in which users commit to the UCC.

4.1 Validation

The aim of this study is to provide insights into good business models for a UCC. To achieve this goal, the setup of the study should be closely related to practice. In this setup, we discuss the steps that we have taken to validate the match between our simulation model and the real world.

The problems that we study are motivated by practice and affirmed by the propositions posed in literature. Also, the measures that we evaluate are existing in the real-world. For our default setting, we consider the measures that are currently in effect in the city of Copenhagen. The other measures that we test are implemented or have been implemented in other Western-European cities; it is conceivable that these measures are implemented in Copenhagen as well. To select appropriate levels for the parameters and variables in our simulation model, we collect data both from a variety of literature sources and directly from industry; we provide a detailed description of our data collection in Section 4.3.

To validate both the data and our experimental setup, we conducted expert interviews with two parties. The first expert represents Binnenstadservice (Dutch for 'Inner City Service'), which operates 15 UCCs in the Netherlands. The second expert is from the municipality of Copenhagen, who is involved with local regulations and logistics initiatives.

To present our virtual UCC in a realistic manner, we draw upon some properties of *Citylogistik-kbh*, the real UCC operating in Copenhagen. Despite similarities such as the physical location, the UCC that we study in this paper is a fictive one; *Citylogistik-kbh* was not involved in this research.

4.2 Test instance

In this section, we provide the context of urban freight logistics in the city of Copenhagen. The measures currently applied in the city are used to define the default scheme; the performance under this scheme is used as a benchmark to evaluate the effects of alternative measures.

Copenhagen is the capital of Denmark and is located on the island of Zealand. The city itself has about 600,000 inhabitants, whereas almost 2 million people live in the Greater Copenhagen region. Copenhagen has a medieval city center with an area of 1 km^2 (Geroliminis and Daganzo 2005). About 500 retailers are located in this area; on a daily basis 6,000 trucks enter the center. Trucks may only visit stores in this area between 9.00 and 11.00am. The larger low-emission zone harbors approximately 2,000 retailers; trucks require a certificate to enter this zone. To be eligible to obtain the certificate, a truck must either be equipped with an effective particle filter or meet Euro 4 emission standards or higher. Currently, the city of Copenhagen charges €12.5 for the certificate, which is valid during the entire lifetime of the vehicle. The administrator is actively involved in reducing the impact of urban freight transport and has implemented or considered various interventions in the past. In 2002, Copenhagen implemented a zone access fee scheme, based on vehicle properties and average capacity utilization (Geroliminis and Daganzo 2005). The city was also involved in starting *Citylogistik-kbh*, which like many other UCCs struggles to generate a sufficiently high throughput. The vast majority of goods destined for the city center (i.e., goods originating from other regions in Denmark or from elsewhere in Europe) arrives via the E20, a highway located south of Copenhagen. *Citylogistik-kbh* is located close to this highway; we assume the same location for our fictive UCC. In Figure 2, we highlight the key characteristics of the case instance. Using the properties of the city of Copenhagen helps to construct a realistic test instance, which we use to test various urban logistics schemes.

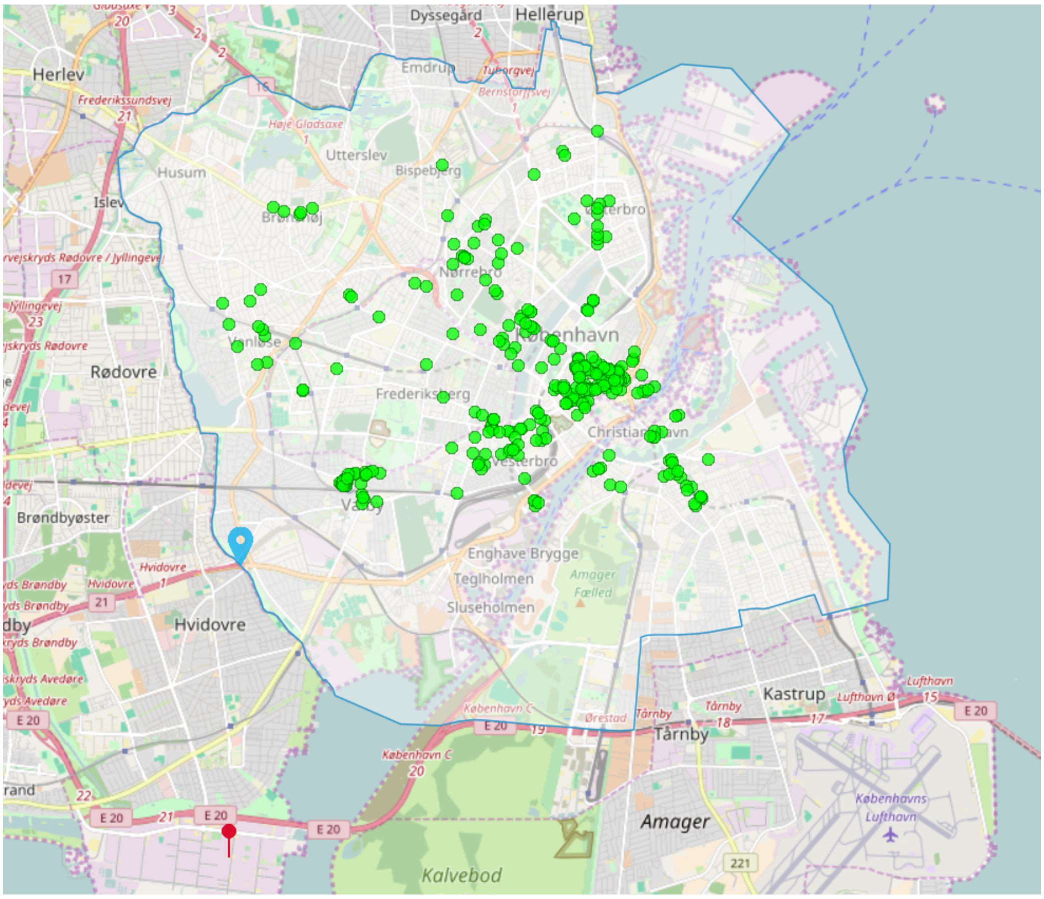

Figure 2: *Map of Copenhagen, indicating the low-emission zone (shaded area), the UCC location (red pin marker), the entrance point for carriers arriving via the E20 (large blue marker), and the receiver locations (green dots)*

4.3 Data collection

Our primary data sources are documents from the Green Logistics project and the BESTUFS project (Browne et al. 2005, Schoemaker et al. 2006, Allen et al. 2008); both projects aggregated real-life data from many different cities and sources. We complement our data set with a number of smaller studies, as well as secondary sources of publicly available data. To obtain data that best represents the case of Copenhagen, we restrict ourselves to the data available for Western European cities. Furthermore, we exclude data corresponding to freight flows that do not fit the scope of this study, such as full truckload transport, construction logistics, and transport of perishable goods.

The data sources reveal great variations in urban logistics metrics, while some parameters lack proper documentation. This makes it challenging to select representative parameters for our simulation study. For certain parameters, we must therefore make justified assumptions on what our representation of reality looks like. The data set that we constructed has been validated during the expert interviews; various parameters were altered to obtain a closer fit with practice. We proceed to discuss our data set in the remainder of this section.

4.3.1 Network design

We obtain retailer locations in the low-emission zone from OpenStreetMap. To create a list of retailer locations, we looked for all addresses within the area labeled as 'shop'. Many shops do not fall into the target group of a typical UCC, which focuses on non-perishable goods that do not require any special sort of care or handling. For example, transporting food would require cooling installations both in the UCC and in the trucks, whereas the transport of jewelry brings a high risk of theft. To distill a representative target group for the UCC, we removed stores falling into the following categories: (i) food (e.g., seafood), (ii) high-value goods (e.g., jewelers), (iii) breakable goods (e.g., glaziers), (iv) fresh goods (e.g., florists), and (v) services (e.g., hairdressers). After this selection, we are left with a set of 1071 retailers. This set consists primarily of (i) fashion (clothes and shoes), (ii) bicycle stores, (iii) convenience stores and kiosks, and (iv) specialized stores (e.g., consumer electronics, sports stores). It is unrealistic to assume that freight flows related to all these retailers might be handled by the UCC. For example, Van Duin et al. (2010) state that a participation of about 10% is a realistic figure for UCCs. A successful example, such as the UCC in La Rochelle – which is heavily supported by regulations and subsidies – handles 30% of freight transport to the city (Browne et al. 2005). We adopt the figure of 30% as an upper bound for the size of the target group in our simulation study. Hence, to generate our test instance, we randomly select 30% of the retailers from our set of shops, leaving us with 321 retailer locations. We use the OpenStreetMap routing implementation of Luxen and Vetter (2011) to compute the travel times between all origin-destination pairs, adopting a driver profile that reflects a vehicle driving close to the maximum allowed speed. The generated travel times take into account factors such as the configuration of the street network, speed limits, and restrictions such as one-way streets.

4.3.2 Receiver properties

The properties of the individual retailers are not directly available; both literature and expert interviews emphasize that the order patterns of retailers are subject to much variability. To model the receivers in a representative way, we collect aggregate data from literature. The order patterns and demands for value-adding services are highly unique. Rather than focusing on specific retail branches, we instead introduce various retailer profiles based on order patterns and demands for value-adding services. From the observed data, we distill the following properties that define a receiver profile: (i) average order volume, (ii) average order frequency, (iii) number of suppliers, and (iv) demand for value-added services.

The first three properties are related to each other, and they depend for a significant part on whether the receiver has a centralized or a decentralized supply system (Cherrett et al. 2012). In centralized supply systems, the receiver usually has a single supplier or logistics service provider that is responsible for all deliveries. Such supply chains tend to be characterized by relatively few deliveries and higher volumes, as consolidation already takes place upstream. To account for the correlation between these properties, we distinguish between receivers based on their supply system. Based on Cherrett et al. (2012), for centralized systems we estimate the average number of deliveries per week at 4.05, whereas receivers with decentralized supply systems receive an average of 11.65 deliveries per week. We establish ranges from which we draw the order frequency and number of distinct shippers that the receiver orders at, these are shown in Table 2. We assume that the ratio between receivers with centralized and decentralized supply chains is 50/50. In practice, the target group of the UCC may contain relatively more receivers with decentralized supply chains, which likely increases the profitability of the UCC due to the higher number of delivery stops made by the carriers. Thus, our assumption of a 50/50 ratio implies a safety margin for our results. Furthermore, we assume that every receiver has 3-5 ordering moments per week, but the centralized profiles (i-iii) place orders with one supplier at a time (averaging to $4 \approx 4.05$ deliveries per week), whereas decentralized profiles (iv-vi) place orders with 2-4 distinct suppliers at a single decision epoch (averaging to $12 \approx 11.65$ deliveries per week). The order volumes are drawn from two empirical distributions (one for centralized and one for decentralized supply chains) that are based on the data of one of the Dutch UCC facilities.

Next, we consider the demand for value-adding services. To the best of our knowledge, there is no literature that quantifies the demand, cost levels and price levels for value-adding services. Our interviews reveal that demand is highly receiver-specific, both in terms of the required services and willingness to pay. Based on price data from the Dutch UCC, we categorize three levels of demands in terms of willingness to pay. Again, we distinguish between receivers with centralized and decentralized supply systems; both may be combined with one of three demand levels for value-adding services. This yields a total of six receiver profiles. In Table 2, we show the properties of the receiver profiles. Receiver-specific values are drawn randomly from the indicated ranges, assuming uniform distributions.

Finally, based on Van Duin et al. (2010), we set the personnel costs for a retailer at €15.3/hour. These costs are relevant to monetize the time that a retailer spends on receiving goods, as well as the time a staff member must be present before the opening time of the shop in case of early deliveries. The average unloading time lies in the range of 7-34 minutes (Schoemaker et al. 2006, Allen et al. 2008). Contrary to what might be expected, deliveries of larger volumes do not translate into longer unloading times (Cherrett et al. 2012). As many factors (e.g., accessibility, handling equipment, quality checks) may influence both the total unloading time and the time the receiver itself is actually involved, we (i) randomly assign an unloading time to receivers from the indicated range (as experienced by the carrier) and (ii) randomly select a value between 2 minutes and the generated total unloading time to indicate how much time the receiver spends on unloading.

4.3.3 Carrier properties

We proceed to describe the properties of carriers. First, we need to establish the number of carriers in our simulation model. With our demand settings and distribution of receiver profiles, about 2,500

Table 2: *Summary of the receiver profiles.*

Profile	Order frequency per week	# orders placed per ordering moment	Demand value-adding services per week	% of total receivers
i	[3-5]	[1]	[€0]	10%
ii	[3-5]	[1]	[€6-20]	37.5%
iii	[3-5]	[1]	[€60-150]	2.5%
iv	[3-5]	[2-4]	[€0]	10%
v	[3-5]	[2-4]	[€6-20]	37.5%
vi	[3-5]	[2-4]	[€60-150]	2.5%

deliveries per working week take place for the target group. Based on Browne et al. (2005), Allen et al. (2008), and Roca-Riu and Estrada (2012), we find that the average number of stops per carrier visiting a city is approximately 10. As we are primarily interested in small, independent carriers, we select the number of carriers such that every carrier uses one truck on average for a delivery route. To achieve this average, we set the number of carriers in our simulation to 50. The number of trucks actually deployed depends on the realization of order demand; a carrier may simultaneously deploy multiple trucks. As mentioned before, the total number of trucks entering Copenhagen is much higher; indeed most carriers and receivers would not fall in the target group of a UCC.

As the transport market is characterized by high competition and high substitutability, we assume that all carriers are homogenous. We suppose that all carriers use medium-sized vehicles with a capacity of 28 m^3. Emission data is obtained from Boer et al. (2011), based on engine standards that are set for the year 2020. The cost parameters are itemized in hourly costs (mainly driver's wage, including unloading time) and costs per km (diesel and depreciation). The corresponding values are obtained from Quak and de Koster (2009) and Roca-Riu et al. (2016), and can be found in Table 3. Recall that the average unloading time at the delivery locations lies in the range of 7-34 minutes. Unlike the receiver, the driver is involved during the complete unloading process, hence the hourly costs are incurred for the duration of the process.

Table 3: *Vehicle properties for carriers (medium-sized truck) and UCC (light truck).*

Vehicle type	Light truck	Medium-sized truck
Load capacity (m^3)	18	28
Driver's wage (€/hour)	21	21
Costs urban transport (€/km) (excluding driver's wage)	0.72	0.86
CO_2 (g/km)	455-553	821-1,065
SO_2 (mg/km)	3.5-4.2	6.3-8.1
NO_x (g/km)	1.5-1.8	2.7-3.5
$PM_{2.5}$ (mg/km)	35-37	53-59

4.3.4 UCC properties

The operational costs of the UCC can be divided into two components, handling costs and transport costs. Table 4 summarizes the components. In the handling costs, we include the costs made at the facility in a broad sense, e.g., rent, insurance, equipment for material handling, and personnel hours. As these cost components are highly dependent on the setup of the UCC, it is difficult to accurately estimate handling costs. In our simulation model, we represent orders by means of volume. Therefore, when sources state handling costs per item rather than per volume unit (e.g., costs per parcel), assumptions on our part are required for the conversion from costs per item to costs per m^3. Furthermore, the available figures may include a transport cost component that is not quantified; based on preliminary experiments, we estimate the transport costs for last-mile deliveries performed by the UCC at €8 per m^3. We stress that we only use this figure to adjust the handling cost estimates of literature sources; in the simulation itself we compute the transport costs by solving its routing problems. The price levels and cost levels that are time-varying are updated as described in Section 3.2.

In a feasibility study, Van Duin et al. (2010) provide a detailed breakdown of the costs of a UCC, with the costs being related to the volumes handled by the UCC. Browne et al. (2005) provide several cost figures from UCCs in practice as well. By triangulating the estimates obtained from these sources with the expert estimates, we estimate the costs of goods handled at the hub. As indicated by Van Duin et al. (2010), handling costs strongly depend on the volumes handled and the corresponding economies of scale; we estimate handling costs at €20/m^3 for a UCC without any agents committed (i.e., the initialization of the handling costs) and €7/m^3 if all orders are delivered via the UCC. The updating procedure of the handling costs over time has been described in Section 3.2. Since data regarding the operational costs of UCCs is both scarce and subject to high variance, we test two additional cost ranges in our experiments, which are based on various literature sources.

We propose that the UCC uses small trucks for the last-mile distribution. Although smaller transport modes – such as bicycles and delivery vans – are often used for urban logistics initiatives, their inability to handle pallets and rolling containers has been identified as a hampering factor in binding UCC users (Van Duin et al. 2010). An additional effect is that due to the small load capacities, the amount of vehicles required vastly increases. Heavy trucks are also unsuitable for last-mile distribution, given their negative impact on traffic and the environment. Hence, in line with Van Duin et al. (2010), we assume that the UCC operates a fleet of light trucks with a loading capacity of 18 m^3. We use the same data sources as for the carrier; the vehicle parameters for light trucks can also be found in Table 3. Finally, we estimate that the upper bounds for the costs of the UCC to perform the value-adding services fall in the range of 70% to 95% of the costs the receiver makes to perform these services in-house, these upper bounds are generated randomly for each receiver. The lower bounds are equivalent to 0.8 times the upper bounds. Thus, in the best case, the UCC can perform the value-adding services at $0.8 \cdot 70\% = 56\%$ of the in-house costs.

We set the prices imposed by the UCC based on data provided by the UCC and the expert interviews. The exact price levels and pricing methods cannot be disclosed for confidentiality reasons, yet the indicated ranges are representative for real life. Receivers always pay a monthly fee for the base service of the UCC (i.e., bundled deliveries); the fee is independent of its location and the volumes delivered. We set the price range for the base service for receivers at €60-70 per month. Carriers that make use of the UCC must pay per outsourced delivery stop. The corresponding price range is set at €12-18 per stop. Finally, value-adding services are a significant source of income, the UCC makes a profit of 25% on these services. Thus, to compute the prices for these services, we set them at 1.25 times the costs that the UCC incurs to perform them.

Table 4: Summary of UCC cost- and price components

Component	Value	Description
Costs transport	0.72 €/km+21€/hour	Route-dependent
Costs handling	7-20 €/m^3	Depending on volume ratio, excluding transport
Costs value-adding services	56-95% of in-house costs	Depending on volume ratio, max. 20% reduction
Price carriers	€12-18 per stop	Depending on volume ratio
Price base service receivers	€60-70 per month	Depending on volume ratio
Price value-adding services	125% of costs	Depending on costs value-adding services

4.3.5 Administrator properties

Aside from implementing regulations, the main design choice for the administrator is how to distribute subsidies. One might think of various distribution keys that encourage a certain behavior, e.g., subsidy based on the forwarded volume, the number of trucks, or time-varying subsidies. A good subsidy scheme should be in accordance with three principles: (i) it should be simple and predictable to create valid business models, (ii) it must not favor or discriminate against individual actors (as this is politically prohibited), and (iii) it should be feasible to implement and to verify (e.g., the administrator should be able to check if allocation criteria are satisfied). In our simulation model, subsidies are provided to agents as a fixed percentage of the UCC price charged to the agents using the UCC, thereby essentially serving as a price discount to the end-users. For receivers, the subsidy is based only on the price for the basic last-mile delivery service, not the prices for value-adding services. This price-based distribution key is simple, does not discriminate among agents, and its allocation can be verified by the administrator. In our simulations, we assume that the subsidy scheme is terminated after two years.

4.4 Scenarios

We conclude this section by outlining our scenarios. We introduce seven test variables (indicated by the capital letters A-G), for which we evaluate three different levels corresponding to 'low' (I), 'medium' (II), and 'high' (III) estimates of the variable. An exception is variable B, which only has two levels. The variable levels are shown in Table 5; every unique combination of variables represents a scheme. We apply a full factorial design, which gives us $2^1 \cdot 3^6 = 1,458$ schemes to evaluate. If possible, we select the variable levels based on the collected data and the expert interviews. However, preliminary experiments indicate that several variables are particularly prone to changes, such that small changes in their values may lead to different outcomes. To provide insight in the impact of setting alternative levels for these variables, we perform sensitivity analysis in Section 5.3.

Table 5: Variable levels

Indicator	Variable	Level I	Level II	Level III
A	Access times	7.00-9.00am	9.00-11.00am	No restrictions
B	Zone access fee	€0		€7
C	Subsidies carriers	0% of costs per outsourced stop	10% of costs per outsourced stop	20% of costs per outsourced stop
D	Subsidies receivers	0% of costs base service	10% of costs base service	20% of costs for base service
E	Subsidies UCC	0% of prices charged for base service and outsourced stops	10% of prices charged for base service and outsourced stops	20% of prices charged for base service and outsourced stops
F	UCC handling costs	2-11 €/m^3	7-20 €/m^3	26-56 €/m^3
G	Margin value-adding services	0%	25%	50%

The expert interviews revealed that the municipality has limited power to implement regulations, as they are bound by government laws. This view is confirmed by the study of Gammelgaard (2015). Measures such as, e.g., city access exclusively for electric trucks, are not viable in the foreseeable future. In this study, we therefore restrict ourselves to measures that are perceivable in the context of urban freight logistics within Denmark, either currently or in the near future.

We start by describing the administrative measures. As mentioned, Copenhagen currently allows vehicles to deliver in the medieval center only between 9.00 and 11.00am. Although this restriction keeps the city free of trucks for most of the day, it may also cause inefficiencies when a carrier has to visit multiple receivers, possibly requiring additional vehicles. Our first test variable (A) therefore relates to the adjustment of this access time restriction. Van Duin et al. (2010) study a variant of access time restrictions, in which they set the latest allowed access time before the opening times of the shops. This requires shop personnel to be in early to receive the goods, thus requiring extra salary payments. This approach is adopted in La Rochelle as well, with the UCC being exempted from the time restriction (Browne et al. 2005). We test this measure to evaluate how it compares to the current access time restrictions, requiring receivers to assign a staff member for two additional hours on delivery days. Another measure that we test is to completely abandon access time restrictions; the potential efficiency losses may outweigh the intended benefits. The second restriction – corresponding to test variable (B) – is the zone access fee for trucks, which in the current situation in Copenhagen is valid for the entire low-emission zone. As stated before, a certificate to gain access to the low-emission zone costs €12.5 and is valid for the lifetime of the truck. For trucks that regularly visit the city, the costs per visit are negligible; we therefore set the current access costs equal to 0. In our simulation, we test the impact of raising the fee. In 2002, the city of Copenhagen charged €7 for a one-day access certificate (OECD 2003); this fee was intended for trucks that did not meet certain vehicle criteria. We use this value as the high variable level for the zone access fee, with the smaller UCC vehicles being exempt from paying the fee.

Next, we discuss the subsidy measures that we test. Although the municipality expert indicated that the willingness to subsidize UCC initiatives is currently low, subsidy schemes are common in many comparable initiatives (Browne et al. 2005). We therefore consider subsidies as a realistic measure. Also, the Danish Transportation Authority was prepared to fund *Citylogistik-kbh* for three years, after which it was supposed to be financially sustainable (Gammelgaard 2015). Ultimately, *Citylogistik-kbh* went private after two years. As stressed in our literature review, subsidies should indeed be of a temporary nature. In our experiments, we assume a two year subsidy period. Traditionally, it is the UCC that receives subsidies, yet these could also be awarded to receivers or carriers for utilizing the UCC. Subsidizing carriers (variable C) or receivers (variable D) could generate initial commitment from these parties, which may aid to reach the critical mass of users and sufficiently lower the cost structure of the UCC to be sustainable when subsidies are halted. Both agent types receive a monthly subsidy when using the UCC; all subsidies stop after two years. Variable E represents subsidies awarded directly to the UCC.

The operational costs of the UCC have a strong impact on its performance; as noted before, the obtained estimates for these costs vary widely. With variable F, we set three cost ranges that represent an upper and lower bound for the handling costs, with the handling costs per m^3 decreasing linearly with the increase in volume handled (see Section 3.2). This variable helps us to determine what the costs for a UCC should be to perform in a sustainable manner. Finally, variable G tests the impact of the profit margin that the UCC makes on value-adding services; we test profit margins of 0%, 25%, and 50%.

5 Results

In this section, we present the results of our simulation experiments. First, we address the financial performance of the individual agents in Section 5.1. Section 5.2 discusses the impact that the various schemes have on the environment. We perform sensitivity analysis on several variables in Section 5.3. In Section 5.4, we discuss the key findings and pose a number of propositions.

Each simulation run represents a time period of five years. Subsidies may be awarded in the first two years, the third year is simulated for the system to stabilize and to reach a steady state. To compute the KPIs, we use the final two years of the simulation. We compare the KPIs obtained for all tested schemes to the performance under the default scheme, in which the city can be accessed by carriers between 9.00 and 11.00am (A_{II}), there is no zone access fee (B_I), there are no subsidies (C_I, D_I, E_I), and the UCC has handling costs between 7 and 20 €/m^3 (F_{II}) and a profit margin on value-adding services of 25% (G_{II}). Comparing KPIs to this default scheme provides insights into the financial performance of the agents. We take the average performance of all agents for a given agent type to compute the performance indicators.

5.1 Financial performance

In this section, we discuss how the financial performance of carriers, receivers, and the UCC is affected by adjusting the variable levels. First, we summarize the performance per agent type for all simulate schemes. Second, we show the effects of changing variable levels, both in isolation and in combination with other measures. Third, we illustrate the performance difference for the UCC between carrier-oriented schemes and receiver-oriented schemes. Fourth, we discuss the properties of the scheme under which the UCC performs best financially, assuming default cost settings.

We discuss how the financial performance of each agent type is affected by adjusting the variable levels. Figure 3 shows the financial performance per agent type (excluding the administrator) for the tested schemes; to aid the visual presentation only every 7^{th} data point is displayed. A positive percentage implies an improvement for the financial KPIs for carriers and receivers (i.e., cost reductions) and for the UCC (net cost reduction, with a cost reduction greater than 100% implying that the UCC makes a profit). A performance below the 0% line implies that the agent loses money compared to the default scheme and would likely oppose the scheme in real life (with the exception of the administrator). The solid horizontal line at 100% indicates the break-even point for the UCC, e.g., the point at which its income (excluding subsidies) equals its costs. The scenarios are sorted from high to low based on the performance of the UCC. Based on our analysis, the main findings with respect to financial performance are that (i) it is challenging to find schemes that result in a profitable UCC (most performances are below the break-even line), (ii) receivers are very inclined to use the UCC when shifted access time windows are introduced, (iii) carriers strongly benefit from the UCC under receiver-oriented schemes, as they can freely outsource their last-mile distribution, and (iv) the schemes under which the UCC performs best are schemes under which carriers considerably improve their performance and receivers improve marginally. Various correlations can be observed in Figure 3. On the far left side, we see the results for the schemes under which the UCC performs best. We see that for these schemes, carriers considerable reduce their costs, whereas receivers are not worse off than under the default scheme. In the remainder of the graph, we observe that when receivers bear all the costs of the UCC due to opting in early (performance indicators are about 12% below the 0% line), the carriers perform very well as they can freely outsource their distribution, while the UCC performs poorly as it obtains its income only for the receivers.

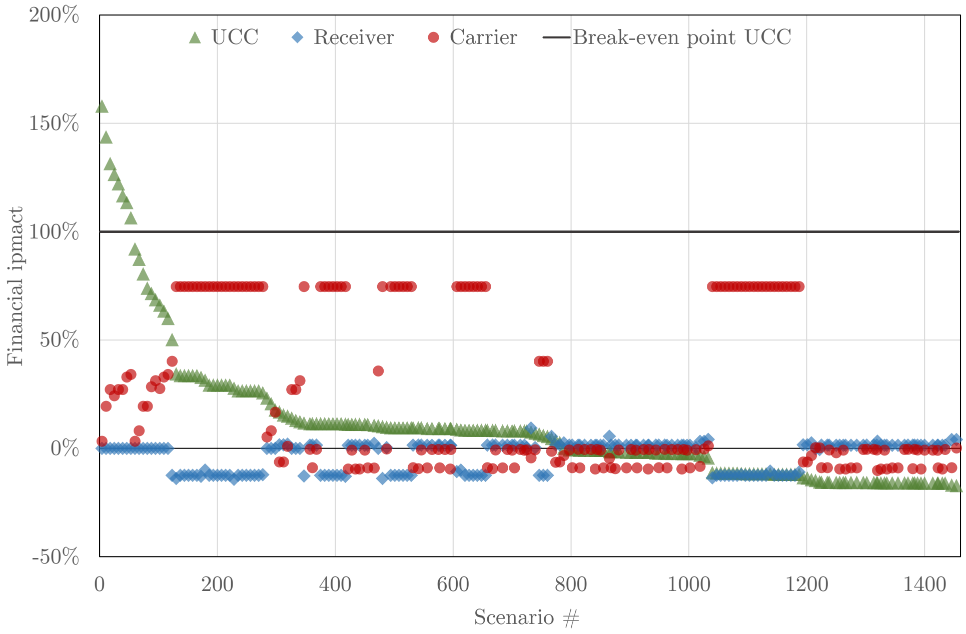

Figure 3: *Financial performance, segregated per agent type for all scenarios. Performance is relative to the default scenario, which is indicated by the 0% line; percentages higher than 0% indicate an improvement. The break-even point for the UCC is indicated by the line at 100%.*

In Table 6, we show the impact of changing each variable on the financial KPIs. For the carriers, receivers, and the UCC, we show four measures for every low and high variable level. First, we show the isolated effect, which we compute by only changing the level of a single variable, with all other variable levels set at their default levels. Second, we compute the main effect, which is the average difference between all pairs of equivalent schemes; each pair contains one scheme in which the variable level of interest is adjusted, whereas in the other scheme of the pair it is set at the default level. Third, we show the worst-case effect. As for the main effect, we compute the differences between pairs, but rather than taking the average, we show only the worst result. Fourth, we compute the best-case effect similarly to the worst-case effect, now only showing the best result. A positive sign indicates a performance improvement. To complement Table 6, Figure 4 graphically represents the main effects per variable level for the carriers, receivers, and the UCC.

We reflect on the influence of each variable. Shifting time windows (A_I) is a very effective measure to commit receivers to the UCC; as the trucks operated by the UCC are exempt from the access time windows, the receiver does not need to dedicate additional personnel hours when outsourcing. The consequence, however, is that carriers can outsource their last-mile distribution for free. As a result, UCCs are typically not able to generate sufficient income in schemes that contain this measure. Removing time access restrictions (A_{III}) on average results in 6 less carriers selecting the UCC, which ultimately translates into higher losses for the UCC. Imposing a zone access fee (B_{III}) results in a higher use of the UCC when combined with other measures; as a stand-alone measure it does not suffice to make carriers adjust their behavior. We have tested six settings related to subsidies (C_{II},C_{III},D_{II},D_{III},E_{II},E_{III}). Both subsidizing carriers and subsidizing the UCC seems to have a positive effect on the financial performance of carriers, receivers and the UCC. However, it appears that subsidizing the UCC is less efficient than subsidizing carriers; a higher expenditure is required to obtain the same net effect. Subsidizing receivers does not yield a positive effect; the resulting cost reduction on the base service is only a small component of their overall costs, and value-adding services are not subsidized. The effect of receiver subsidies on the number of receivers joining is therefore negligible. For all subsidy measures, we see that they have a limited impact as a stand-alone measure; they must be combined with other measures to achieve the desired outcomes, otherwise agents simply revert to their former behavior after the subsidy period ends. Adjusting the estimated handling costs at the UCC (F_I and F_{III}) has a considerable impact on the financial performance of the UCC, with an average improvement of 36% in the net result for the low-cost setting and a 41% reduction of the net result for the high-cost setting. The experimental results imply that sustainable UCC schemes do not exist for the high-cost setting. The final variable that we consider is the profit margin of value-adding services (G_I and G_{III}). Varying the profit margin has an impact on the net income of the UCC. However, as in profitable schemes only about 15% of the revenue stems from value-adding services, the overall impact of varying the profit margin remains relatively small. To summarize, most measures have a limited effect when implemented on a stand-alone basis (only the shift of time windows has a considerable impact on all agent types), but in combination with other measures particularly subsidies (to UCC and carrier) and zone access fees generally have a positive impact. Later in this section, we list the parameter settings that correspond to the best performing scheme under average cost settings.

Table 6: *Financial impact per variable level, segregated per agent type [Receiver, carrier, UCC]. Figures marked gray indicate a minor impact on the financial KPI (between -5% and 5%), red indicates a major negative impact (-5% or worse), and green indicates a major positive impact (+5% or better).*

Variable level	**Isolated effect**	**Main effect**	**Worst-case effect**	**Best-case effect**
A_I	[-14%,75%,9%]	[-14%,72%,-49%]	[-25%,35%,-1245%]	[-10%,78%,25%]
A_{III}	[0%,-2%,-3%]	[0%,-3%,-41%]	[-3%,-55%,-1129%]	[5%,17%,5%]
B_{III}	[0%,-5%,-4%]	[0%,-6%,14%]	[-11%,-136%,-4%]	[4%,35%,563%]
C_{II}	[1%,-1%,-2%]	[0%,3%,4%]	[-9%,-4%,-2%]	[2%,40%,122%]
C_{III}	[1%,-1%,-2%]	[1%,8%,24%]	[-9%,-136%,-2%]	[2%,37%,163%]
D_{II}	[6%,-5%,-2%]	[0%,0%,-1%]	[-4%,-8%,-50%]	[6%,8%,38%]
D_{III}	[3%,-3%,0%]	[0%,1%,-3%]	[-6%,-5%,-75%]	[7%,12%,38%]
E_{II}	[3%,0%,-3%]	[0%,3%,4%]	[-10%,-3%,-3%]	[4%,37%,129%]
E_{III}	[1%,-1%,-2%]	[1%,8%,24%]	[-9%,-136%,-4%]	[4%,40%,163%]
F_I	[0%,0%,5%]	[0%,0%,36%]	[0%,0%,5%]	[0%,0%,634%]
F_{III}	[0%,0%,-14%]	[0%,0%,-41%]	[0%,0%,-612%]	[0%,0%,-10%]
G_I	[0%,0%,-1%]	[0%,0%,-3%]	[0%,0%,-63%]	[0%,0%,0%]
G_{III}	[0%,0%,1%]	[0%,0%,5%]	[0%,0%,0%]	[0%,0%,563%]

Key for variable indicators: A=Access time window, B=Zone access fee, C=Subsidy carriers, D=Subsidy receivers, E=Subsidy UCC, F=UCC handling costs, G=Margin value-adding services.

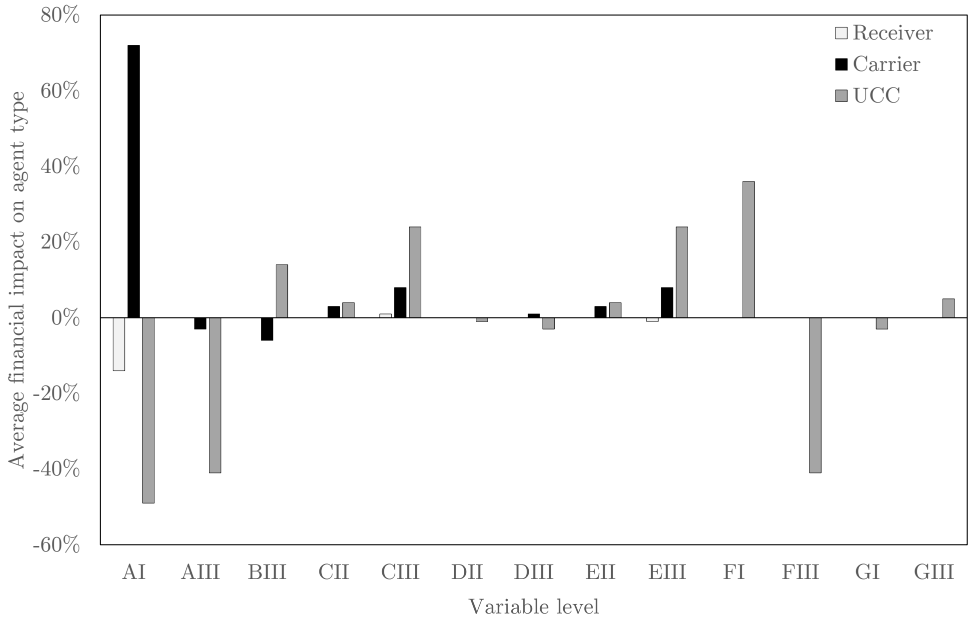

Figure 4: *Barchart, visualizing the financial main effects as listed in Table 6 per variable level for the carriers, receivers, and the UCC.*

Our analysis of the numerical results indicates that the sequence in which UCC users are attracted is decisive for the eventual profitability of a scheme. Figure 5 shows the income and costs for the UCC over time for a scheme that focuses on attracting carriers before receivers, Figure 6 shows the same information for a scheme that aims to attract receivers first. Both schemes assume low costs for the UCC (F_I) and a medium profit margin on value-adding services (G_{II}). It can be seen that the scheme that aims to first commit carriers performs considerably better than the other scheme. Although the latter attracts more users overall, the costs for the UCC are consistently higher than its income, as it generates its income only from the receivers. In the first scheme we observe a drop in the number of committed receivers when the subsidies are ended, yet the UCC remains profitable in the years that follow.

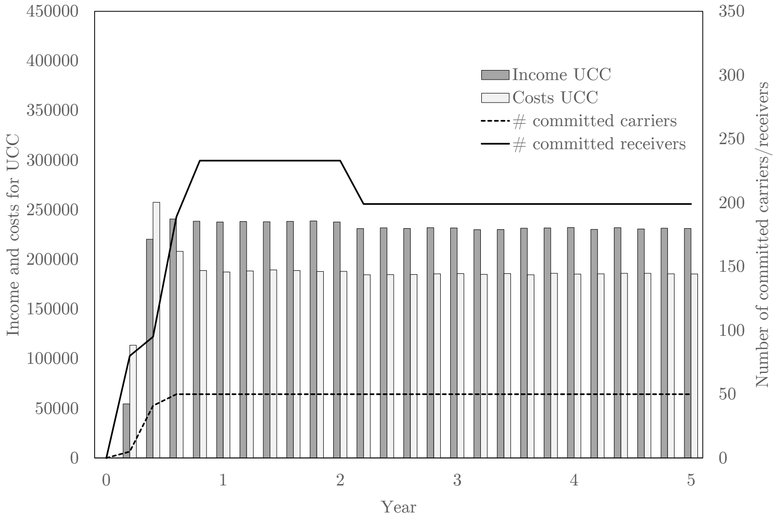

Figure 5: *Financial performance for the UCC under a scheme that primarily aims to attract carriers. Assumed are low handling costs (F_I) and a medium profit margin (G_{II}).*

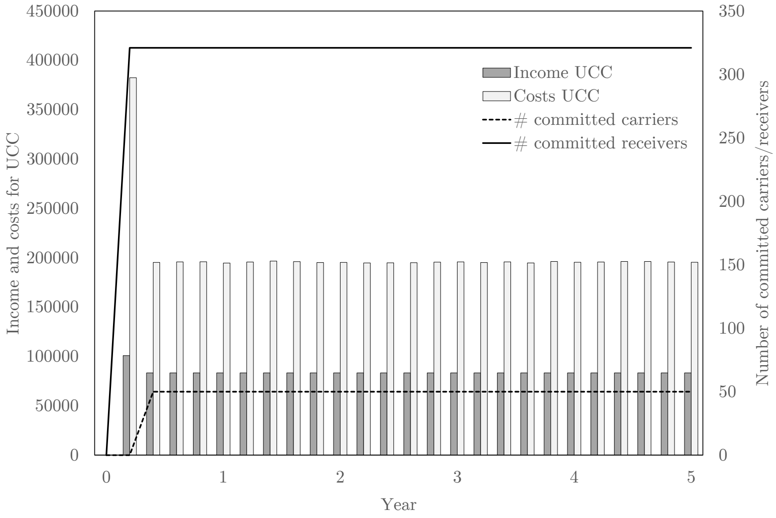

Figure 6: *Financial performance for the UCC under a scheme that primarily aims to attract receivers. Assumed are low handling costs (F_I) and a medium profit margin (G_{II}).*

The objective of the simulation study is to identify schemes that yield a positive net result for the UCC, while not decreasing the financial performance of the other agents. We are primarily interested in whether such schemes exist for medium cost levels for the UCC, i.e., handling costs of

7-20 €/m^3 and a profit margin of 25% on value-adding services. In Figure 7, we show the financial KPIs for the best scheme – in terms of UCC profitability – compared to the performance under the default scheme. Despite being the best performing scheme under default cost settings, it still yields a loss of 8.5% to the UCC. The scheme has the following properties: an access time window from 9.00 to 11.00, 20% subsidies to both carriers and the UCC, and a zone access fee of €7. We observe a cost reduction for the carriers, virtually no cost change for the receivers, and a major reduction in net costs for the UCC. Under the best scheme, the UCC generates considerable more revenue than under the default scheme, while the revenue is also proportionally larger compared to the costs. As stated before, the scheme still yields a loss to the UCC; the only schemes in our simulation that generate a profit are those with low cost settings for the UCC. To see whether slight adjustments of the best scheme may yield a profitable situation for the UCC, in Section 5.3 we finetune several variables to verify whether profits are attainable under average cost settings for the UCC.

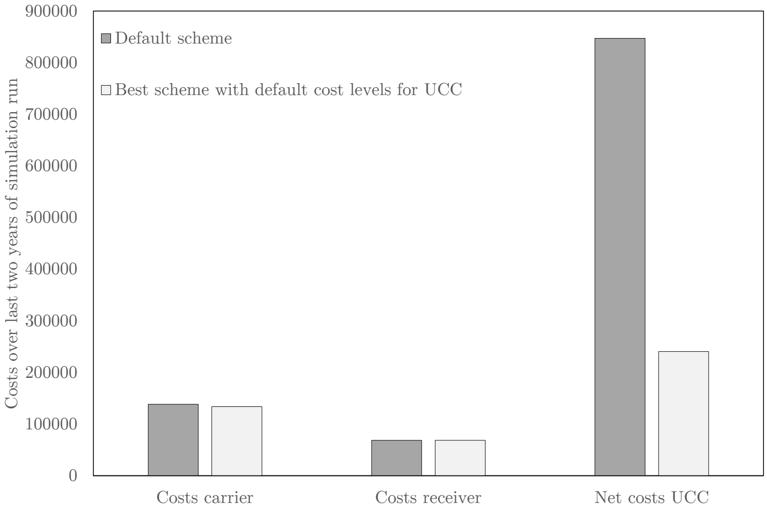

Figure 7: *Financial performance of carriers, receivers, and UCC under both the default scheme and the financially best-performing scheme, both under default handling costs (F_{II}).*

5.2 Environmental performance

In this section, we discuss the environmental performance of the schemes that we tested. First, we discuss the environmental impact of all simulated schemes. Second, as we have seen that most schemes perform poorly from a financial point of view, we reflect on the relation between financial and environmental performance, and show the environmental impact of the scheme under which the UCC performs best financially.

As the emission levels are measured based on distance and the emission ratios between the two truck types for CO_2, SO_2, NO_x, and $PM_{2.5}$ are almost equivalent, the individual emission levels would be hard to graphically distinguish. Therefore, we aggregate them for the sake of our virtual representation. Figure 8 shows the average emission levels that correspond to the schemes; again, only 1 in 7 data points are displayed. The emission levels are normalized with respect to those of the default scheme, which are set equal to 100%. Furthermore, the average emission level for the scenario without UCC is indicated by the horizontal lines. The scenarios are sorted based on their resulting emission reduction. It can be seen that considerable reductions in emissions are achievable; the left side of the graph shows emission reductions for schemes with high utilization of the UCC. From an environmental perspective, all schemes perform better than in the scenario without a UCC. The best schemes reduce emissions by approximately 70% compared to the default scenario. Furthermore, such schemes reduce the total number of trucks in the city – i.e., both from carriers and the UCC – by up to 60% and the total distance driven by up to 65% (not shown in the figure). These considerable benefits indicate that the concept of a UCC makes sense from an environmental perspective.

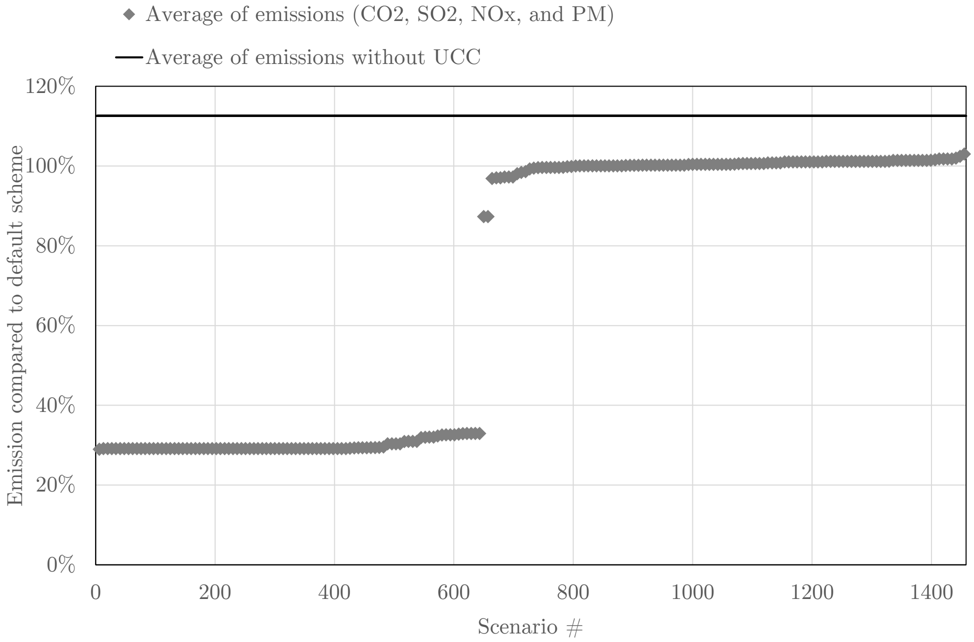

Figure 8: *Average emission levels compared to the default scheme for all tested schemes. The 100% line indicates the emission levels under the default scheme, values below 100% indicate an improvement. The average emission levels without a UCC are shown by the solid line.*

Although many schemes strongly improve the environmental performance, it is challenging to find a scheme that is also financially viable. However, when a scheme performs well financially, this also implies a good environmental performance. Financial results depend on attracting a sufficiently high number of UCC users, such that a considerable number of stops is outsourced to the UCC. The inverse relation between environmental and financial performance is not necessarily true: a scheme may perform well from an environmental perspective, but be unsustainable financially, e.g., when committing all receivers before the carriers join.

In Table 7, we compare the environmental KPIs for the financially best-performing scheme (see Figure 7) to the KPIs under the default scheme. The difference between both schemes shows a considerable improvement on all KPIs. Compared to the default scheme, the best scheme reduces emission levels by 68% up to 72%. Although the number of small trucks in the city increases due to the higher use of the UCC, the total number of trucks reduces by 61%, whereas the total distance driven decreases by 67%.

Table 7: *Performance on environmental KPIs compared between the default scheme and the financially best-performing scheme. All outcomes correspond to the final two years of the simulation.*

KPI	**Default scheme**	**Best scheme**	**Change**
CO_2 (ton)	383.51	70.42	72%
SO_2 (kilogram)	2.92	0.53	72%
NO_x (ton)	1.26	0.23	72%
$PM_{2.5}$ (kilogram)	22.97	4.99	68%
# small trucks	2,937	11,493	-291%
# large trucks	26,244	0	100%
Total # trucks	29,181	11,493	61%
Distance small trucks (×1000km)	38	139	-261%
Distance large trucks (×1000km)	385	0	100%
Total distance trucks (×1000km)	423	139	67%

5.3 Sensitivity analysis

Although we strive to use data that reflects the real world as accurately as possible, the nature of our simulation study inherently requires simplifications and assumptions on the real-world variable levels. A full factorial design for a large number of values per variable would be computationally intractable. In this section, we therefore test the impact of variables that are both subject to considerable variability and are expected (based on preliminary tests) to have a significant impact on the results. For each variable that we test, we simulate with multiple numerical values for the variable of interest, while keeping all other variables at their default levels. We perform sensitivity analysis on the following variables: (i) the width of the access time windows, (ii) the subsidy levels to the carrier, and (iii) the price that the UCC charges to the carriers. Furthermore, we finetune several variables in the financially best-performing scheme, as this scheme – under average cost settings – yields financial losses for the UCC.

The access time restriction of two hours that is currently applied in the city of Copenhagen appears to be ineffective to persuade carriers to use the UCC. We test the impact of various widths of the time access window on the number of carriers that commit to the UCC. The results are shown in Figure 9. We see that windows with a width up until one hour have the intended effect; for larger windows the number of committed carriers becomes lower. When access time restrictions are used as a standalone measure, windows wider than two hours do not aid in attracting carriers to utilize the UCC.

We have already established that subsidies as an independent measure are not sufficient to permanently attract carriers; they need to be combined with other measures to yield a sustainable solution. More specifically, to reach a steady state in which the UCC makes a profit, the carriers should be attracted before the receivers, and subsidy levels should be set in accordance with this goal. Nevertheless, it remains useful to know the smallest subsidy amount that the administrator needs to spend in order to commit carriers within a certain subsidy period. In Figure 10, we show the impact of 10 different subsidy levels on the commitment of carriers over time, measured during

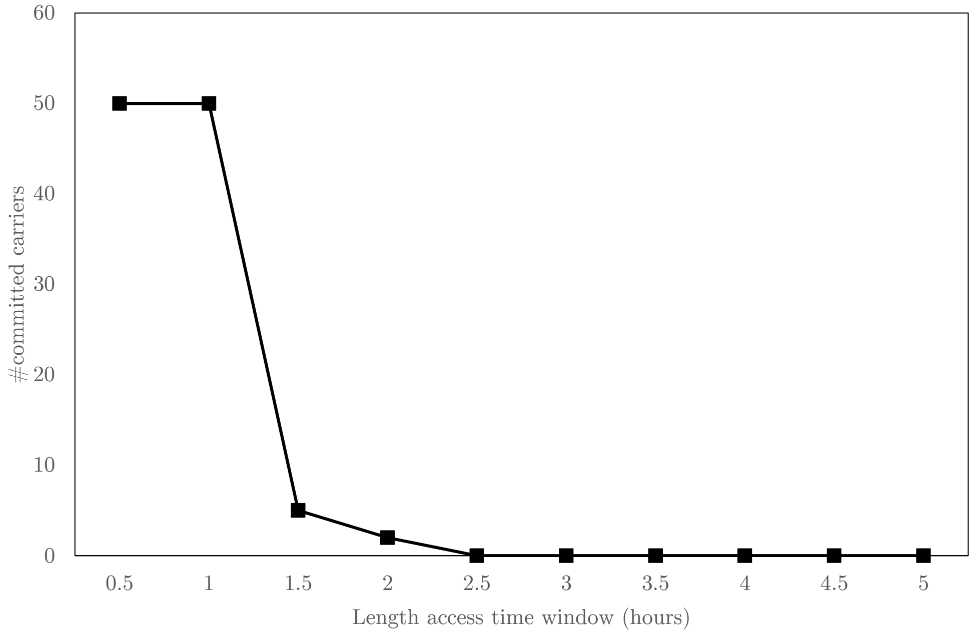

Figure 9: *Impact on the number of committed carriers for a variety of access time window widths.*

the two-year subsidy period. We see that for levels over 12%, half a year of subsidies suffices to attract all carriers. For a level of 12% it takes one year; levels lower than 12% fail to attract all carriers within two years. To attract higher numbers of carriers directly at the start, subsidies higher than 20% are required; these levels are not shown in the figure.

Analysis of our results indicates that the carriers are very price-sensitive. Figure 11 shows the effects of various price levels on the commitment of carriers to the UCC under the base scenario. In contrast to the price bounds used in the main experiments, for this sensitivity analysis we assume a fixed price that is not altered over time. For price levels higher than €9.5 per stop, the number of carriers that use the UCC rapidly declines. However, at price levels of €9.5 and below, the UCC is not financially sustainable; a higher price in combination with supporting measures is required to ensure the required income for the UCC.

We conclude this section with an evaluation of the impact of finetuning the best performing scheme (see Figure 7), as the achieved net profit of -8.5% is insufficient for the UCC to survive in the long term. Recall that this scheme has an access time window from 9.00 to 11.00, 20% subsidies to both carriers and the UCC, and a zone access fee of €7. We finetune various cost and subsidy variables, and highlight the adjustments that resulted in a positive profit. In terms of profit, increasing subsidy levels for either the UCC or the carriers from 20% to 30% yields the best results. This change instantly commits almost all carriers from the start – such that the profit from this group is maximized – and results in a positive profit margin of 12.1% for the UCC. Another successful measure is to lower the price of the base service from €60-70 to €40-50. These lower costs

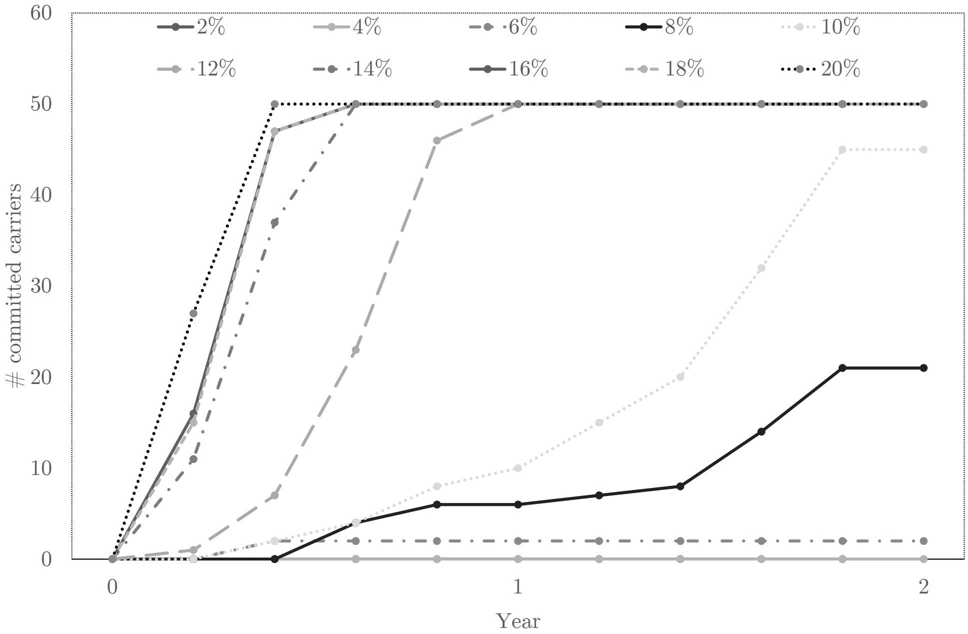

Figure 10: *Impact on the number of committed carriers for a variety of subsidy levels.*

result in 15% more receivers in the steady state and push the profit margin of the UCC to 2.2%. Finally, raising the zone access fee for from €7 to €9 yields a profit margin of 0.3% for the UCC, due to committing several extra carriers in the early stages. The impact of these measures show that relatively small price changes may impact the profitability of the UCC considerably.

5.4 Discussion

In this section, we reflect on the key insights obtained from the numerical experiments, provide a number of propositions with respect to good business models for UCCs, and discuss the impact of discrepancies between reality and the simulation model. We stress that a solid business model requires both a good financial performance and a good environmental performance. As mentioned before, a scheme that attracts high numbers of UCC users implies good environmental performance, but is not necessarily financially viable.

Proposition 1: The commitment of carriers to the UCC should be ensured before targeting the receivers.

The numerical results show that in the most successful schemes, the bulk of the carriers commit to the UCC before the receivers do. As carriers only pay for outsourcing stops at receivers that have not committed to the UCC at the time of the tactical decision, first committing the carriers maximizes the revenues stemming from this group. Subsequently, value-adding services may still be

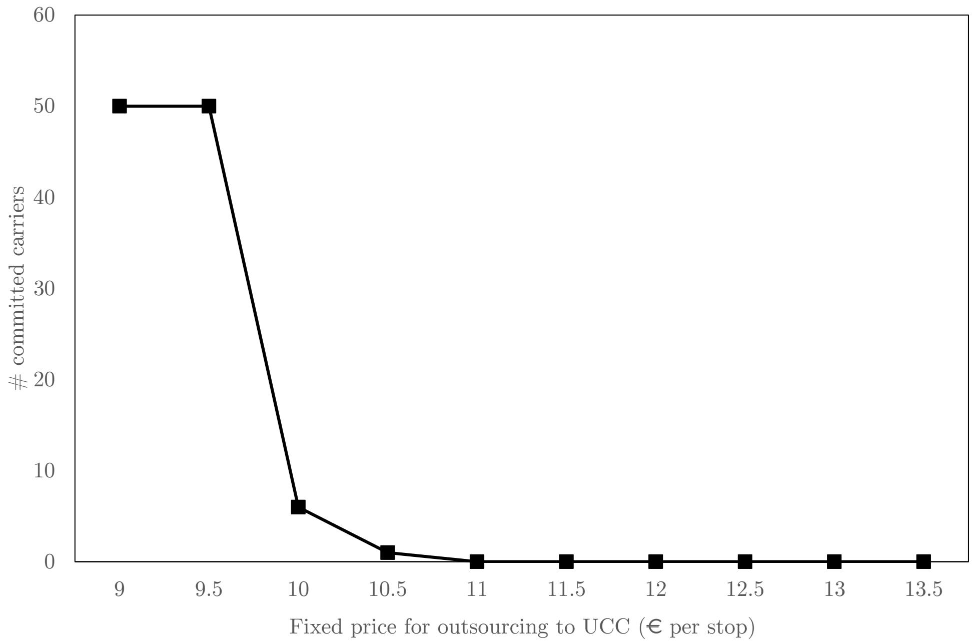

Figure 11: *Impact on the number of committed carriers for a variety of price levels.*

sold to the receivers. At that point in time, the UCC already handles larger volumes due to the committed carriers, enabling to offer lower prices to the receivers. After the startup years, the UCC should be able to offer sufficiently competitive prices such that carriers remain users of the UCC.

Proposition 2: Subsidies are most effectively allocated to the carriers.
As stated in Proposition 1, carriers should be the primary target for a UCC that aims to attract a user base. Allocating subsidies to the carriers appears to be the most effective measure to achieve this goal. The subsidies should be sufficiently large to commit many carriers within a relatively short period of time. The numerical results show that relatively high subsidies are necessary for this purpose. Subsidies that are allocated to the UCC have similar effects as subsidizing the carriers, but in a less efficient manner. Subsidies allocated to receivers are less effective, as attracting receivers before carriers negatively affects total revenues.

Proposition 3: Access time restrictions only aid the UCC if the access window is set sufficiently narrow.
When an access time window is used as a stand-alone measure, the current width of two hours is ineffective for the purpose of committing carriers to the UCC. Particularly when part of the receivers outsource their last-mile distribution to the UCC, the access restrictions are not stringent for carriers. However, in combination with other measures, access time windows appear to have a positive effect on the usage of the UCC.

Proposition 4: Setting access time restrictions before the opening times of stores is an effective measure to generate commitment from receivers.
Setting the time access restrictions before the opening times of stores requires receivers to dedicate additional personnel for receiving goods, unless it outsources the last-mile delivery to the UCC; the small vehicles operated by the UCC are exempt from the access time windows. This makes it a very effective measure to commit receivers to the UCC. Although successful in attracting receivers, this measure tends not to create viable schemes. When receivers commit to the UCC before carriers do, revenues can no longer be obtained from carriers, as for them the UCC has already become the final delivery address.

Proposition 5: Zone access fees can have a positive effect in combination with other measures.
As a stand-alone measure, zone access fees at their current level are ineffective in realizing a change in the behavior of carriers. However, in combination with other measures, zone access fees may have a modest positive effect on the utilization of the UCC, as they increase the costs for carriers and therefore make the UCC prices more favorable. For carriers that need to make only few stops in the city, the zone access fee is a relatively large component of their costs, which makes such carriers more inclined to outsource their shipments to the UCC.

We acknowledge that our simulation model deviates from practice on various aspects; we discuss the impact of the two most important deviations. First, for the performance of the UCC in our simulation model, the sequence in which carriers and receivers commit to the UCC is very important. Due to instantaneous decision making by the agents combined with varying price levels, decisions made in the early stages of the simulation greatly impact the steady-state performance of the UCC. Although it is obvious that decisions made in practice will be more gradual and involve negotiations with the UCC, the main takeaway remains that the focus should be on attracting carriers first as they generate the bulk of the revenue for the UCC, and that administrative measures should be in support of this approach. A second deviation from practice is that we assume price ranges that vary based on the volumes that are handled by the UCC. Although the underlying argument of economies of scale holds for the operating costs, in practice the continuous price changes would likely cause confusion for the UCC users and require frequent contract renegotiations. The main reason for using ranges rather than fixed price levels is that they make it easier to identify steady states, rather than finding them by means of trial-and-error. As fixed price levels may only work for a specific scheme, it is difficult to make generic statements regarding single price levels.

6 Conclusions

In this paper, we presented an evolutionary simulation study on the feasibility of a starting UCC under a variety of urban logistics schemes. We have designed an agent-based simulation model, which represents receivers, carriers, the UCC, and the local administrator as autonomous entities. Decisions within the simulation are divided into three levels: strategic, tactical, and operational. The strategic level represents the subsidy schemes and regulations implemented by the administrator.

On the tactical level, subsidies and UCC price levels are adjusted. Subsequently, receivers and carriers decide whether or not to join the UCC based on their expected costs. Finally, on the operational level routing decisions are made and handling cost are computed, allowing to calculate the operational costs of the agents. The goal of the study was to identify schemes that – after an initial subsidy period – enable all agents to operate in a financially sustainable manner, while simultaneously yielding substantial environmental improvements.

The simulation study has been applied on a case inspired by the city of Copenhagen, Denmark. Based on a known OpenStreetMap implementation, we generated a realistic network to represent the city. We have gathered data to accurately portray the agents via various meta-studies, individual case studies, and publicly available information. Both the setup of the case study and the reliability of the data have been validated by means of expert interviews. We created receiver profiles to reflect the large variance between receivers in practice, thereby generating diversity in the simulated supply chains.

We have tested 1,458 different schemes, for which we measured both financial and environmental KPIs. We have shown that considerable environmental improvements may be achieved through the use of a UCC, reducing the number of trucks in the cities by up to 60% and reducing emissions by about 70%. However, it is challenging to find schemes that are also financially sustainable. We showed that the UCC can obtain the highest revenues by first convincing carriers to outsource their stops, and then selling value-adding services to the receivers in the city. The concept of the UCC appears to be unsuccessful without supporting measures; temporary subsidies to the carriers and imposing a zone access fee appear to be the most effective measures in achieving a steady state in which the UCC is profitable and can eventually operate without external funding, once having received a sufficient scale of operations.

Acknowledgments

This research is partially funded by JPI Urban Europe. We gratefully acknowledge the support of Binnenstadservice Nederland in providing data and its contributions to the experimental setup. Finally, we thank the Copenhagen municipality in providing valuable feedback on our experimental setup.

References

Allen, J., Browne, M., Cherrett, T., and McLeod, F. (2008). Review of UK urban freight studies. *Green Logistics project, Universities of Westminster an Southampton.*

Allen, J., Browne, M., Woodburn, A., and Leonardi, J. (2012). The role of urban consolidation centres in sustainable freight transport. *Transport Reviews*, 32(4):473–490.

Ambrosino, G., Boero, M., Di Bugno, M., Guerra, S., and Librato, A. (2007). A centre for eco friendly city freight distribution: Urban logistics innovation in a mid-size historical city in Italy. *ICL 2007.*

Bektaş, T., Crainic, T. G., and Van Woensel, T. (2015). From managing urban freight to smart city logistics networks. *CIRRELT 2015-17.*

Boer, E., Otten, M. B. J., and Essen, H. (2011). *Comparison of various transport modes on a EU scale with the STREAM database.* CE Delft.

Browne, M., Sweet, M., Woodburn, A., and Allen, J. (2005). Urban freight consolidation centres. *Transport Studies Group*, 10.

Cherrett, T., Allen, J., McLeod, F., Maynard, S., Hickford, A., and Browne, M. (2012). Understanding urban freight activity–key issues for freight planning. *Journal of Transport Geography*, 24:22–32.

Crainic, T. G., Ricciardi, N., and Storchi, G. (2004). Advanced freight transportation systems for congested urban areas. *Transportation Research Part C: Emerging Technologies*, 12(2):119–137.

Dablanc, L. (2011). City distribution, a key element of the urban economy: guidelines for practitioners. In Macharis, C. and Melo, S., editors, *City distribution and urban freight transport: Multiple perspectives*, pages 37–56. Edward Elger, Cheltenham, UK.

Gammelgaard, B. (2015). The emergence of city logistics: the case of Copenhagens Citylogistik-kbh. *International Journal of Physical Distribution & Logistics Management*, 45(4):333–351.

Geroliminis, N. and Daganzo, C. F. (2005). A review of green logistics schemes used in cities around the world.

Huschebeck, M. and Allen, J. (2004). BESTUFS policy and research recommendations I: urban consolidation centres, last mile solutions.

Kin, B., Verlinde, S., Van Lier, T., and Macharis, C. (2016). City vehicle routing problem (city VRP): A review. *Transportation Research Procedia*, 12:357–369.

Luxen, D. and Vetter, C. (2011). Real-time routing with OpenStreetMap data. In *Proceedings of the 19th ACM SIGSPATIAL International Conference on Advances in Geographic Information Systems*, GIS '11, pages 513–516, New York, NY, USA. ACM.

OECD (2003). *Delivering the Goods: 21st Century Challenges to Urban Goods Transport.* OECD Publishing, Paris.

OSM Foundation (2017). OpenStreetMap. `https://www.openstreetmap.org/about`. Accessed: 2017-01-04.

Quak, H. J. (2008). *Sustainability of urban freight transport: Retail distribution and local regulations in cities*. EPS-2008-124-LIS. Erasmus Research Institute of Management (ERIM).

Quak, H. J. and de Koster, M. B. M. (2009). Delivering goods in urban areas: how to deal with urban policy restrictions and the environment. *Transportation Science*, 43(2):211–227.

Roca-Riu, M. and Estrada, M. (2012). An evaluation of urban consolidation centers through logistics systems analysis in circumstances where companies have equal market shares. *Procedia-Social and Behavioral Sciences*, 39:796–806.

Roca-Riu, M., Estrada, M., and Fernández, E. (2016). An evaluation of urban consolidation centers through continuous analysis with non-equal market share companies. *Transportation Research Procedia*, 12:370–382.

Schoemaker, J., Allen, J., Huschebek, M., and Monigl, J. (2006). Quantification of urban freight transport effects i. *BESTUFS Consortium, www. bestufs. net.*

Tamagawa, D., Taniguchi, E., and Yamada, T. (2010). Evaluating city logistics measures using a multi-agent model. *Procedia-Social and Behavioral Sciences*, 2(3):6002–6012.

Taniguchi, E., Thompson, R. G., and Yamada, T. (2014). Concepts and visions for urban transport and logistics relating to human security. In Taniguchi, E., Fwa, T. F., and Thompson, R. G., editors, *Urban transportation and logistics: Health, safety, and security concerns*, pages 1–30. CRC Press, Boca Raton, USA.

Transmodal, M. (2012). DG MOVE European Commission: Study on urban freight transport.

United Nations (2014). Worlds population increasingly urban with more than half living in urban areas. `https://www.un.org/development/desa/en/news/population/world-urbanization-prospects.html`. Accessed: 2016-03-22.

Van Duin, J. H. R., Quak, H. J., and Muñuzuri, J. (2010). New challenges for urban consolidation centres: A case study in The Hague. *Procedia-Social and Behavioral Sciences*, 2(3):6177–6188.

Van Duin, J. H. R., van Kolck, A., Anand, N., and Taniguchi, E. (2012). Towards an agent-based modelling approach for the evaluation of dynamic usage of urban distribution centres. *Procedia-Social and Behavioral Sciences*, 39:333–348.

Van Heeswijk, W. J. A., Mes, M. R. K., and Schutten, J. M. J. (2016). An agent-based simulation framework to evaluate urban logistics schemes. *Lecture Notes in Computer Science*, 9855:369–383.

Van Rooijen, T. and Quak, H. J. (2010). Local impacts of a new urban consolidation centre–the case of Binnenstadservice.nl. *Procedia-Social and Behavioral Sciences*, 2(3):5967–5979.

Verlinde, S., Macharis, C., and Witlox, F. (2012). How to consolidate urban flows of goods without setting up an urban consolidation centre? *Procedia-Social and Behavioral Sciences*, 39:687–701.

Wangapisit, O., Taniguchi, E., Teo, J. S., and Qureshi, A. G. (2014). Multi-agent systems modelling for evaluating joint delivery systems. *Procedia-Social and Behavioral Sciences*, 125:472–483.