DTU Library

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

van Heeswijk, Wouter; Larsen, Rune; Larsen, Allan

Link back to DTU Orbit

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

Wouter van Heeswijk, Rune Larsen & Allan Larsen

Published online: 22 Feb 2019.

Submit your article to this journal ⬀

Article views: 581

View Crossmark data ⬀

Citing articles: 1 View citing articles ⬀

Taylor & Francis
Taylor & Francis Group

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

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

[a]Department of Industrial Engineering and Business Information Systems, University of Twente, Enschede, the Netherlands; [b]Department of Management Engineering, Technical University of Denmark, Lyngby, Denmark

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 often prevent attracting a sufficient number of UCC users. In this paper, we study sustainable business models and the supporting role of administrative policies. We perform an agent-based simulation applied to the city of Copenhagen and collect data from a variety of sources to model 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. Most schemes yield significant environmental benefits; many of them 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 the importance of committing carriers to the UCC as soon as possible, as carriers potentially generate the bulk of the revenue. 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 (United Nations, 2014). Therefore, the retail sector in cities is growing fast as well, causing an increase in the volumes of urban freight transport (Transmodal, 2012). Spurred by the fierce competition with e-commerce and expensive in-shop storage (due to high real estate prices), just-in-time principles gain popularity among retailers, resulting in low storage levels, small order volumes, and more frequent orders (Crainic et al., 2004). Retailers nowadays often impose narrow delivery windows and expect fast delivery. In addition, stricter regulations enforced by municipalities limit transport accessibility to urban shopping areas. Due to these developments, freight flows are becoming increasingly fragmented, making it difficult to plan efficient routes for small freight carriers in particular; such carriers comprise about 85% of the transport market (Dablanc, 2011).

The surge in the number of freight transport movements has a hazardous impact on public health, the environment, and the quality of life in urban areas. Freight transport comprises about 15% of total traffic in cities, yet causes up to 50% of traffic emissions and disproportionally contributes to external costs such as noise hindrance, road congestion, and traffic safety (Dablanc, 2011). 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). Heavy truck transport therefore has a considerable impact on congestion in streets and shopping areas.

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. Urban consolidation centers (UCCs) have a central role in many solution concepts to reduce the impact of urban freight transport (Quak, 2008; Transmodal, 2012). A UCC located at the edge of the city enables inbound trucks to unload without entering the city and to perform last-mile transport in an efficient and environmentally friendly manner. Especially for inbound trucks with poor capacity utilization, significant efficiency gains may be made by bundling goods into a single delivery vehicle. 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. Overdependence on subsidies also is a common pitfall for UCCs. Recent research implies that combining bundling with initiatives such as off-hour deliveries while providing appropriate incentives might aid users' adoption (Marcucci & Gatta, 2017). This is particularly true for retailers who perceive the combined measure as both feasible and convenient (Holguín-Veras, 2008). Examples of currently stable

operating UCCs are Binnenstadservice in the Netherlands, Gnewt Cargo in the UK, and CityDepot in Belgium; common characteristics is that they lack permanent subsidies and offer extensive value-adding services (Bohne et al., 2015).

Most successful schemes combine company-driven initiatives with government policies (Browne et al., 2005). The commitment of companies is essential, yet supportive regulation and subsidies are typically required as well. Despite a handful of successful UCCs being in existence, knowledge of 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, due to available expertise for this city, as well as having representative properties of a typical European city (e.g., moderate size, historical city center, pedestrian streets). We use 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.

This paper aims to contribute to literature by identifying sustainable business models for UCCs and the administrative measures that best support such models. Although several studies have been performed on the subject, they typically consider small, simplified networks, test only few scenarios, and do not model agents in accordance with data obtained from practice. As such, they ultimately offer few insights into good practices for UCCs and how to deploy administrative policies to elevate UCC success rates. This study offers new insights by performing experiments on an instance based on realistic data, validating the experimental setup via expert interviews, and testing over 1400 scenarios.

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. The main conclusions are presented in Section 6.

2. Literature review

A UCC is a logistics facility that is located in the proximity of an urban area, allowing to decouple and bundle inbound freight flows (Browne et al., 2005). By consolidating shipments a UCC may perform last-mile delivery more efficiently than individual carriers (Huschebeck & Allen, 2004; Quak & de Koster, 2009). In addition, the UCC may dispatch small and environmentally friendly vehicles more suitable for last-mile delivery. The potential benefits are highest when considering freight flows that are inefficiently organized (Browne et al., 2005; Van Rooijen & Quak, 2010). Verlinde et al. (2012) point out 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.

On a high level, two business models for UCCs can be distinguished (Van Rooijen & Quak, 2010). In the first one, carriers outsource their urban deliveries to the UCC. The costs for last-mile distribution are disproportionally high for carriers, as travel speeds are low, unloading is time-consuming, truck capacity may be significantly underutilized, and local regulations may be restrictive. Despite these incentives, the price of outsourcing is often too high for carriers (Kin et al., 2016; Van Rooijen & Quak, 2010). In the second business model, the receiver in the urban area selects the UCC as its delivery address. By bundling multiple deliveries into one the receiver spends less time (and thus costs) on receiving goods. However, as shipping costs are generally embedded in order prices, outsourcing costs typically exceed the efficiency gains (Verlinde et al., 2012). For the retailer, the key merits of the UCC are value-adding services such as (i) temporary storage, (ii) waste collection, (iii) e-tailing logistics, (iv) home deliveries, and (v) specialized services such as splitting pallets into smaller loads or putting clothes on hangers (Allen et al., 2012; Van Rooijen & Quak, 2010).

Municipalities often incorporate administrative measures to reduce the negative effects of heavy freight transport, which may be beneficial for UCCs. Quak and de Koster (2009) divide administrative measures into three classes, namely (i) road pricing (e.g., a price per kilometer for certain vehicle types), (ii) licensing and regulation (e.g., truck bans, license fees or limited access times based on weight or engine class), and parking and unloading (e.g., a dedicated unloading bay for small trucks). By working with light and environmentally friendly vehicles, the UCC may obtain a competitive advantage over larger trucks used by carriers.

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. 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). The aforementioned sources indicate that UCCs are often unable to generate a sufficiently high throughput to reach the break-even level required for a sustainable business model. The inability to attract sufficient users is partially caused by a lack of external support. In the startup phase of a UCC, municipalities often provide subsidies. When this financial support is ended, the UCC is often unable to survive (Browne et al., 2005; Kin et al., 2016). Permanent subsidy schemes rarely exist in practice (Browne et al., 2005), even though such funding might be rationalized by environmental benefits.

As the low success rate of UCCs might suggest, little analysis has been performed on their long-term success factors (Van Rooijen & Quak, 2010). There is often an absence of a clearly defined target group of potential UCC users. Many freight flows are already efficiently organized; transshipments may actually make them less efficient (Van Rooijen & Quak, 2010). Furthermore, retailers, carriers, and municipalities may all benefit in some way from a UCC, yet strive to accomplish divergent objectives (Bektaş et al., 2017). Reducing environmental costs—especially by means of policies—often comes at a financial cost for the actors involved, such that system-wide optimization fails to generate

solutions to which autonomous actors would commit in practice (Geroliminis & Daganzo, 2005). Despite the lack of success of UCCs so far, the concept remains relevant. The aforementioned trend of freight flow fragmentation makes the potential added value of UCCs more prominent than it was in the past. Also, operational costs may be reduced by adopting state-of-the-art technology and by better integrating the handling process within the supply chain (Triantafyllou et al., 2014).

Most UCC studies analyze cases, often evaluating past performances or focusing on best practices. The broadest case study to date is performed by Browne et al. (2005), analyzing 67 schemes throughout Europe. Examples of case studies evaluating one or several UCCs are Marcucci and Danielis (2008) (Fano), (Triantafyllou et al. 2014) (Southampton), Nordtømme et al. (2015) (Oslo), and Van Duin et al. (2016) (London, Bristol, Nijmegen). A number of insights on UCC business models may be derived from these studies. Carriers are particularly skeptical about UCCs, partially because they often view the UCC as a competitor. Existing UCCs therefore tend to focus more often on committing receivers. Financial challenges are very common for UCCs, especially those running without subsidies. Furthermore, proper alignment between policies and the UCC operations appears essential. More broadly speaking, including all stakeholders from an early stage is deemed an important prerequisite for success.

Due to a lack of publicly available data on the operations of UCCs and their business models, some authors turned to modeling to assess the concept of UCCs and obtain new insights. A common modeling approach for UCCs is to reflect their operations as a vehicle routing problem, contrasting the performance of direct transport and transport via the UCC. We highlight some examples. Van Rooijen and Quak (2010) focus on the environmental gains stemming from using the UCC. Jacyna (2013) also zoom in on environmental gains, citing improved material flows and reduced emissions. Roca-Riu et al. (2016) study the feasibility of UCCs from the perspective of collaborating carriers, and state that average distance costs may be reduced significantly. More complex variants consider one or two layers of hubs rather than a single consolidation center. De Assis Correia et al. (2012) study a UCC setting with multiple hubs, and claim that considerable gains can be made in transport efficiency. A two-echelon variant may be found in Hemmelmayr et al. (2012).

A limitation of routing-based approaches is that they only address transport efficiency, ignoring the effects on other stakeholders. Agent-based simulation takes into account such effects. 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; various research efforts have been made in this direction. 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, studying various settings for UCC service fees, road pricing, and subsidies. Wangapisit et al. (2014) research the use of UCCs when combining parking constraints with carrier subsidization. A recent trend foresees the integration of agent-based modeling with discrete choice modeling to characterize agents with utility functions based on stated preference data. See for instance the work of Marcucci et al. (2017), which simulates stakeholders interactions in urban freight transport via opinion dynamics models, taking inspiration from Le Pira et al. (2017).

The goal 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.

3. Methodology

As stated in the previous section, agent-based simulation is a suitable tool to analyze urban logistics schemes. For this study we apply the agent-based simulation framework of Van Heeswijk et al. (2016). This framework explicitly focuses on the synergy between business initiatives and administrative policies. Also, it segregates decision-making into various time periods of commitment, corresponding to the process that we aim to emulate. The agent types included in the framework are receivers, carriers, the UCC, and the municipality, all pursuing their own objectives within the constraints of the system. We selected these agent types, as together they abstractly represent the dynamics of transport decisions within the city. The receivers, carriers, and UCC form a basic transport system, with the receivers and carriers both having a direct influence on the system. Demand and supply patterns are assumed to be given, which is why shippers are not included in the model. Finally, the municipality indirectly represents the interests of stakeholders such as residents, but also exercises a direct influence on the transport system.

At the heart of the framework is a discrete-event simulation over a finite decision horizon, with $\mathcal{T} = \{0, 1, ..., T\}$ representing a set of decision epochs separated by 1-day intervals. There are three levels of decision-making (strategic, tactical, and operational), which we discuss 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 $\mathcal{T}^{tac} \subset \mathcal{T}$ and in this study are fixed for two months. 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. Section 3.3 describes 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 street network 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).

We discuss six key assumptions. First, all orders that are generated at a given decision epoch are delivered before the subsequent decision epoch, significantly speeding up the simulation. The limited delivery windows allow for less bundling flexibility for the UCC; in practice higher efficiencies

might be achieved. Second, all agents update their tactical decisions at the same decision epochs, again chiefly considering computational speed. This assumption may cause more fickle behavior by the agents, however, we note that agent behavior eventually converges to a steady state. Third, order frequencies and order volumes of receivers are fixed during the simulation. O'Rourke (2014) states that the retail sector moves to demand-driven supply chains, in which customer demand is a leading factor for their order patterns. The potential drawback in the simulation is that retailers may fail to adopt cheaper order policies. Fourth, receivers and carriers make their decisions whether to join the UCC independent of each other (i.e., with respect to decisions made at the same epoch), eliminating the need to model responsive agent behavior. Although simplifying reality, the expert interviews confirm that users generally have little knowledge regarding the negotiations between UCC and other parties. Fifth, costs decrease when the amount of volume handled by the UCC increases, reflecting economies of scale. For the UCC, such economies of scale are confirmed both by literature (e.g., Kin et al., 2016; Malhene et al., 2012; Van Duin et al., 2010; Van Duin et al., 2016; Verlinde et al., 2012) and the expert interviews, although the magnitude and curve depend on the UCC-specific equipment and operations. Literature is inconclusive on the curve shape of economies of scale; only on the bounds we can make justified assumptions. In this paper, we assume a linear relation between costs/prices and the volume ratio. Price levels are adjusted relative to the costs, and are therefore also linear with respect to the volume. Sixth, if a user commits to the UCC, all its shipments are handled by the UCC until the next tactical decision moment. In practice, users may wish to only outsource part of their loads. This paper only models the smaller flows for which outsourcing is of interest, leaving larger truckloads outside of the scope. Our assumption reflects the practice in which user and UCC typically sign a contract for a fixed period of time during which a predetermined set of loads or customers is agreed to be outsourced. For example, a carrier may contractually agree to outsource loads for various small customers, while delivering larger customers itself. Note that if a receiver commits to the UCC, the carrier is only obliged to deliver shipments destined for this specific receiver at 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 $l \in \mathcal{L} = \{\frac{1}{y}, ..., 1\}$ 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 $\omega_t = (\widetilde{I}_{t,c,r,l})_{\forall(c,r,l) \in \mathcal{C} \times \mathcal{R} \times \mathcal{L}}$, 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:

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

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. The binary variable $\gamma_{t,r}^{rec,tr} \in \{0, 1\}$ represents whether receiver r makes use of the base service of the UCC (i.e., bundled deliveries) at time t; the vector $\gamma_t^{rec,tr} = (\gamma_{t,r}^{rec,tr})_{\forall r \in \mathcal{R}}$ stores this information for all receivers. The variable $\gamma_{t,r}^{rec,val} \in \{0, 1\}$ and the vector $\gamma_t^{rec,val} = (\gamma_{t,r}^{rec,val})_{\forall r \in \mathcal{R}}$ have similar purposes, 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 pay the fee for the base service as well, i.e., $\gamma_{t,r}^{rec,val}$ can have a value of 1 if and only if $\gamma_{t,r}^{rec,tr} = 1$. Finally, the variable $\gamma_{t,c}^{car} \in \{0, 1\}$ and the corresponding vector $\gamma_t^{car} = (\gamma_{t,c}^{car})_{\forall c \in \mathcal{C}}$ describe whether the carrier outsources its last-mile transport to the UCC.

To reflect economies of scale for 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. Let $l_{t',t''}^{ucc} \in [0, 1]$—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 $\gamma_t^{rec,tr} = (\gamma_{t,r}^{rec,tr})_{\forall r \in \mathcal{R}}$, the vector of receivers that outsource their value-adding services to the UCC $\gamma_t^{rec,val} = (\gamma_{t,r}^{rec,val})_{\forall r \in \mathcal{R}}$, the vector of carriers that use the UCC $\gamma_t^{car} = (\gamma_{t,c}^{car})_{\forall c \in \mathcal{C}}$, and the volume ratio $l_{t',t''}^{ucc}$. We denote the problem state at time t as

$$S_t = \left(I_t, \gamma_t^{rec,tr}, \gamma_t^{rec,val}, \gamma_t^{car}, l_{t',t''}^{ucc}\right). \qquad (2)$$

3.2. Agent intelligence

In this subsection, we describe the agent intelligence embedded in the simulation model. Small and independent actors typically do 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.

In our simulation, strategic decisions are made only by the municipality. These long-term decisions are fixed at $t = 0$ for the duration of the simulation run and involve deciding on the subsidy levels, setting the length of the subsidy period (after which subsidies are set to 0), determining the accessibility measures to the city, and setting the policy costs. We select administrative measures that are conceivable to be implemented in practice by the municipality of Copenhagen. 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. This measure is close to practice as it is currently in effect in Copenhagen; we test three settings for the access time 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. Currently, the city of Copenhagen works with relatively cheap access licenses for trucks, in the past it also charged higher access fees for certain truck types. The access fee measure is therefore also

consistent with practice. As the UCC uses small trucks, it is exempted from both measures. Finally, the real Copenhagen UCC has been co-funded for a period of 2 years as well.

At the appropriate decision epochs, tactical decisions are made sequentially by the municipality, the UCC, and then (in parallel) by the receivers and carriers. Receivers and carriers make the decision to outsource to the UCC independent of each other. Carriers that are not committed to the UCC are only obliged to visit the UCC to deliver goods destined for receivers that are committed to the UCC. Furthermore, it is possible that both the carrier and the receiver are committed to the UCC, although financial incentives may change if one of the actors is committed. In particular, carriers have little financial incentive to use the UCC if their receivers already pay the UCC for last-mile delivery.

We describe the steps of the tactical decision level. First, the municipality may alter its subsidy levels, which are expressed as a percentage of the price charged by the UCC. If the UCC itself receives subsidies, it lowers its prices proportionally. When the municipality allocates subsidies to multiple agent types, their effect is cumulative, e.g., when both the UCC and the carriers are subsidized for 20%, the effective price reduction is 40% for carriers and 20% for receivers. The subsidy percentages are fixed at the start of the simulation, and are always set to 0% at the end of the
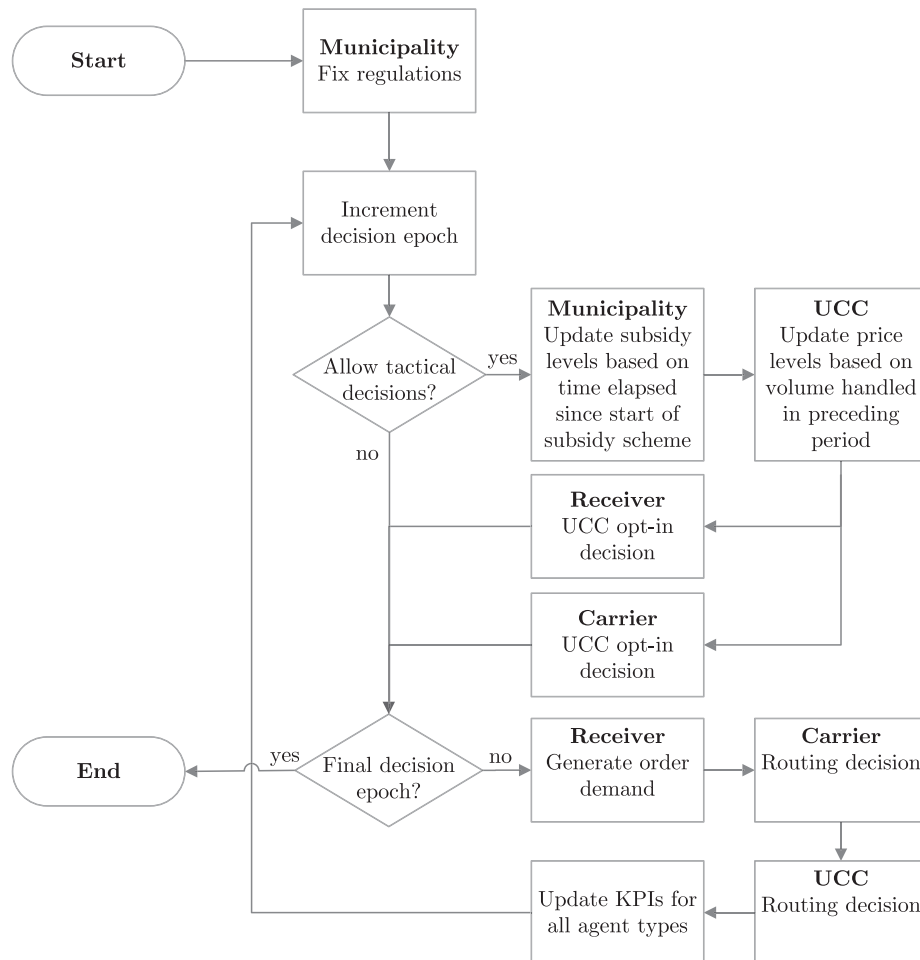

Figure 1. Flowchart of the simulation model.

subsidy period. Second, cost- and price levels of the UCC are adjusted based on the volume ratio $l_{t',t''}^{ucc}$, which has been defined in Section 3.1. This mechanism reflects the economies of scale that are achieved by handling larger volumes. In this section 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. 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 $l_{t',t''}^{ucc}$ determines the price level within this range. We update receiver prices as follows:

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

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. 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 $n \in \{1, ..., N\}$ being the index for the sample path and $t_n \in \{1, ..., \tau^{sample}\}$ being the time index for the sample states of path n. For every $n \in \{1, ..., N\}$, we obtain a set of sample states $\{\widetilde{S}_{t+1_n}, ..., \widetilde{S}_{t+\tau_n^{sample}}\}$.

In each sample state $\widetilde{S}_{t+t_n}$, 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 $\widetilde{\gamma}_r^{rec,tr} \in \{0,1\}, \widetilde{\gamma}_r^{rec,val} \in \{0,1\}$, and $\widetilde{\gamma}_c^{car} \in \{0,1\}$ 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 $\widetilde{C}^{rec}(\widetilde{S}_{t+t_n}, \widetilde{\gamma}_r^{rec,tr}, \widetilde{\gamma}_r^{rec,val})$ and $\widetilde{C}^{car}(\widetilde{S}_{t+t_n}, \widetilde{\gamma}_c^{car})$; 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. The following equations show how we update the tactical decision for the receivers and for the carriers:

$$\left[\gamma_{t,r}^{rec,tr}, \gamma_{t,r}^{rec,val}\right] = \arg \min_{\substack{\sim rec,tr \\ \gamma_r \in \{0,1\}, \\ \sim rec,val \\ \gamma_r \in \{0,1\}}} \frac{1}{N} \sum_{n=1}^{N} \sum_{t_n=1}^{\tau^{sample}} \widetilde{C}^{rec}\left(\widetilde{S}_{t+t_n}, \widetilde{\gamma}_r^{rec,tr}, \widetilde{\gamma}_r^{rec,val}\right)$$

$$\forall r \in \mathcal{R}, \quad (3)$$

$$\gamma_{t,c}^{car} = \arg \min_{\substack{\sim car \\ \gamma_c \in \{0,1\}}} \frac{1}{N} \sum_{n=1}^{N} \sum_{t_n=1}^{\tau^{sample}} \widetilde{C}^{car}\left(\widetilde{S}_{t+t_n}, \widetilde{\gamma}_c^{car}\right) \quad \forall c \in \mathcal{C}. \quad (4)$$

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 & 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 $\Delta_t = \Delta_t^{ucc} \cup \cup_{c \in \mathcal{C}} \Delta_{t,c}^{car}$ 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 with six indicators, namely CO_2 emission, SO_2 emission, NO_x emission, $PM_{2.5}$ emission, the number of vehicles in the urban area (itemized per vehicle type), and the distance covered per vehicle type.

The four different agent types, along with their objectives, constraints and KPIs, are listed in Table 1. We note that—with the exception of the municipality—all objectives are strictly financial, reflecting the fact that the transport sector is mainly cost-driven (Crainic, 2012). Furthermore, considerations such as convenience and reliability are left out as the test setting is typified by hard time windows and deterministic travel times. However, we do note that in practice, convenience and reliability are relevant success factors for

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
Municipality	Minimize environ-Mental costs	Profitability of the agents Functioning supply system	CO_2 (global emissions)
			SO_2, NO_x, $PM_{2.5}$ (local emissions)
			Number of vehicles (per type)
			Total vehicle distance (per type)
			Income administrative policies
			Costs subsidies

UCCs. We are chiefly concerned with the profitability of the UCC; therefore, we set profit maximization as its objective. The revenue operations of carriers and receivers are outside the scope of the model, therefore we adopt a cost-minimizing perspective for these agents. We 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).

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 $\widetilde{\gamma}_c^{car}$. Let $\Delta_{t,c}^{car}|\widetilde{\gamma}_c^{car} = 0$ be the route set corresponding to the case in which the carrier visits all its delivery addresses (possibly including the UCC) itself, and let $\Delta_{t,c}^{car}|\widetilde{\gamma}_c^{car} = 1$ 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 $C^{car,tr}(\Delta_{t,c}^{car}|\widetilde{\gamma}_c^{car} = 0)$ we obtain the transport cost that correspond to the carrier visiting all its delivery addresses itself; $C^{car,tr}(\Delta_{t,c}^{car}|\widetilde{\gamma}_c^{car} = 1)$ 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 $P_t^{ucc,car,tr}(\Delta_{t,c}^{car}|\widetilde{\gamma}_c^{car} = 0)$—the route notation contains the number of stops that are outsourced—and depend on the price charged by the UCC at time t. Finally, $P_t^{car,ucc,sb}(\Delta_{t,c}^{car}|\widetilde{\gamma}_c^{car} = 0)$ 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

$$C_t^{car}\left(\gamma_{t,c}^{car}, \Delta_{t,c}^{car}|\widetilde{\gamma}_c^{car} = 0, \Delta_{t,c}^{car}|\widetilde{\gamma}_c^{car} = 1\right)$$

$$= \left(1-\gamma_{t,c}^{car}\right)C^{car,tr}\left(\Delta_{t,c}^{car}|\widetilde{\gamma}_c^{car} = 0\right) + \gamma_{t,c}^{car}C^{car,tr}\left(\Delta_{t,c}^{car}|\widetilde{\gamma}_c^{car} = 1\right)$$

$$+\gamma_{t,c}^{car}P_t^{ucc,car,tr}\left(\Delta_{t,c}^{car}|\widetilde{\gamma}_c^{car} = 0\right) - \gamma_{t,c}^{car}P_t^{car,ucc,sb}\left(\Delta_{t,c}^{car}|\widetilde{\gamma}_c^{car} = 0\right).$$

The costs incurred by the receiver are comprised of the following five elements: (i) the receiving costs $C^{rec,rc}(r, \Delta_t^{ucc}, \cup_{c\in\mathcal{C}}\Delta_{t,c}^{car})$ incurred for physically receiving deliveries, 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

$$C_t^{rec}\left(r, \gamma_{t,r}^{rec,tr}, \gamma_{t,r}^{rec,val}, \Delta_t\right) = C^{rec,rc}\left(r, \Delta_t^{ucc}, \cup_{c\in\mathcal{C}}\Delta_{t,c}^{car}\right)$$

$$+\left(1-\gamma_{t,r}^{rec,val}\right)C^{rec,val}(r) + \gamma_{t,r}^{rec,tr}P_t^{ucc,rec,tr}$$

$$+\gamma_{t,r}^{rec,val}P_t^{ucc,val}(r) - \gamma_{t,r}^{rec,tr}P_t^{rec,ucc,sb}.$$

For the UCC, transport costs are calculated similarly to those of the carriers and are denoted by $C^{ucc,tr}(\Delta_t^{ucc})$. 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 $C_t^{ucc,hd}(\cup_{c\in\mathcal{C}}\Delta_{t,c}^{car})$ 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 $P_t^{ucc,car,tr}(\Delta_{t,c}^{car}|\widetilde{\gamma}_c^{car} = 0)$, 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:

$$C_t^{ucc}\left(\gamma_t^{rec,tr}, \gamma_t^{rec,val}, \gamma_t^{car}, \Delta_t\right) = C^{ucc,tr}\left(\Delta_t^{ucc}\right)$$

$$+C_t^{ucc,hd}\left(\underset{c\in\mathcal{C}}{\cup}\Delta_{t,c}^{car}\right) + \sum_{r=1}^{|\mathcal{R}|}\gamma_{t,r}^{rec,val}C_t^{ucc,val}(r)$$

$$-\sum_{c=1}^{|\mathcal{C}|}\gamma_{t,c}^{car}P_t^{ucc,car,tr}\left(\Delta_{t,c}^{car}|\widehat{\gamma}_c^{car}=0\right)-\sum_{r=1}^{|\mathcal{R}|}\gamma_{t,r}^{rec,tr}P_t^{ucc,rec,tr}$$

$$-\sum_{r=1}^{|\mathcal{R}|}\gamma_{t,r}^{rec,val}P_t^{ucc,val}(r)-P_t^{ucc,sb}.$$

The final agent type is the municipality. For this agent, we measure the following KPIs, (i) subsidy expenses, (ii) policy income, (iii) emissions, (iv) distance per vehicle type, and (v) number of vehicles per type. We do not assign weights to these KPIs and therefore do not introduce an explicit cost function. Instead, based on a relative comparison between schemes, we monitor whether environmental performance justified the financial costs of the scheme.

4. Experimental setup

In this section, we describe the setup of the simulation study. The goal of the study is to find sustainable business models for the UCC and which combinations of administrative measures best aid such models. 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. Subsidies are awarded for 2 years (equal to the actual subsidy period of the real Copenhagen UCC), implying that the UCC has limited time to create a sufficiently large user base such that the operational costs are low enough to offer competitive prices. Each simulation run represents a period of 5 years; the performance in the last 2 years is used to evaluate whether the UCC achieves the desired performance. Lebeau et al. (2017) state that UCCs could operate stably after 3 years, although longer startup periods are also reported.

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 (as receivers typically do not have direct transport contracts with carriers, see Verlinde et al. (2012)). From this perspective, it is sensible to first generate commitment from the carriers, as this leaves open the possibility of receivers paying 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 (according to the expert interviews). Indeed, Browne et al. (2007) state that receivers typically are the primary source of income for UCCs and list the most benefits for this group of users, although they point out that quantification of the benefits is challenging. We emphasize that there is no general consensus on the user benefits for UCCs; for example, Marcucci and Danielis (2008) state that in fact carriers benefit more than receivers from the UCC. In our simulation, we test a variety of subsidy allocations to observe how they affect the sequence in which users commit to the UCC.

4.1. Validation

This study aims to perform experiments in a setting that is sufficiently close to reality to draw practically applicable conclusions. 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 such measures might be 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 4.2.

To validate the data as well as the experimental setup, we conducted expert interviews with two parties. The first expert represents Binnenstadservice, which operates 15 UCCs in the Netherlands. The second expert is from the municipality of Copenhagen, and is involved with local regulations and logistics initiatives. The interviews consisted of open components for the experts to share their vision on UCC operations and our experimental setup, as well as closed questions on business practice and policy implementation. Finally, we posed specific requests for data on, e.g., costs, prices, and subsidy levels.

Rather than modeling agents based on—often sparse—available data, Anand et al. (2016) propose to model agent behavior on their revealed preferences obtained by stakeholder. We have done so indirectly by consulting the UCC expert and assuming financially rational decision-making. Although this suffices to fill the current gap in literature, follow-up research that consults a larger number of experts might more accurately validate the model and more closely represent reality by adopting a behavioral approach that incorporates, e.g., the willingness to pay for services under varying circumstances.

4.2. Data collection

Our primary data sources are documents from the Green Logistics project and the BESTUFS project (Allen et al., 2008; Browne et al., 2005; Schoemaker et al., 2006); both projects aggregated real-life data from many different cities and sources. 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 outside 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. 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.

4.2.1. Network design

We use OpenStreetMap to obtain retailer locations. Filtering out certain branches unsuitable for UCC distribution, an initial set of 1071 locations remains, consisting primarily of fashion stores, bicycle stores, convenience stores, and specialized stores. Van Duin et al. (2010) state that a participation rate of about 10% is a realistic figure for UCCs. Even heavily supported UCCs such as the one in La Rochelle handle no more than 30% of freight transport to the city (Browne et al., 2005). We do not foresee any scenario in which our fictional UCC in Copenhagen achieves a higher user percentage than that. Adopting the figure as an upper bound, we randomly select 30% of the retailers from our initial location set, leaving us with 321 retailer locations in our test network. In Section 5.2, we test alternative bounds ranging from 10% to 50%. For the UCC location, we use the location of *Citylogistik-kbh*, the UCC currently operating in Copenhagen. We use the OpenStreetMap routing implementation of Luxen and Vetter (2011) to compute the travel times between all origin-destination pairs. 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.

4.2.2. Receiver properties

The properties of the individual retailers are not directly available; both literature and expert interviews emphasize that the order patterns of retailers vary greatly. We introduce six distinct 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 receiver profiles are summarized in Table 2.

The first three properties are correlated and depend on whether the receiver has a centralized or a decentralized supply system (Cherrett et al., 2012). Receiver with centralized supply systems have a single supplier, resulting in relatively few deliveries and higher volumes. We assume that the ratio between receivers with centralized and decentralized supply chains is 50/50. In reality, decentralized supply chains might be more suited for UCC use. However, in

practice supply chains are rarely purely (de)centralized (Cherrett et al., 2012), but some form of hybrid. This makes it difficult to determine the actual ratio. As decentralized systems result in more delivery stops and therefore higher UCC income, the 50/50 ratio implies a safety margin for our results. The sensitivity analysis in Section 5.2 includes various ratios to quantify the effect of this assumption.

Based on Cherrett et al. (2012), we estimate for centralized profiles an average of 4.05 deliveries/week and for decentralized profiles an average of 11.65 deliveries/week. Each receiver has 3-5 ordering moments per week; centralized profiles place orders with one supplier at a time (averaging to $4 \approx 4.05$ deliveries per week) and decentralized profiles place orders with 2–4 distinct suppliers at a time (averaging to $12 \approx 11.65$ deliveries per week). The order volumes are drawn from empirical distributions that are based on the data provided by a Dutch UCC facility.

Next, we consider the demand 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. Table 2 shows the properties of the receiver profiles. Receiver-specific values are uniformly drawn from the indicated ranges.

Finally, based on Van Duin et al. (2010), we set the personnel costs (used to quantify receiving costs) at €15.3/hour. The average unloading time lies in the range of 7-34 minutes (Allen et al., 2008; Schoemaker et al., 2006). Deliveries of larger volumes do not necessarily 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.

4.2.3. 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 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 the transport market is characterized by high competition and high substitutability, we assume that all carriers operate homogenous fleets composed of medium-sized vehicles with a capacity of 28 m^3. This assumption isolates the measured effect of the UCC from the potential mode

Table 2. Summary of the receiver profiles.

Profile	Order frequency per week	No. of 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%

shift. A drawback is that the model does not reflect differences in fleet composition, such that financial and environmental distinctions between modes are ignored in the present study. 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.

4.2.4. UCC properties

We discuss costs and prices of the UCC, the summary can be found in Table 4. The costs of the UCC might be divided into three components, handling costs (including, e.g., rent, handling equipment, and personnel hours), transport costs, and costs for value-adding services. Handling costs strongly depend on the volumes handled and the corresponding economies of scale (Van Duin et al., 2010); estimates in literature vary widely. We estimate handling costs by triangulating the figures provided by Browne et al. (2005) and Van Duin et al. (2010) with the expert estimates. We set 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. Two additional cost ranges based on literature are tested in our experiments.

We proceed with transport costs. In reality, UCCs may deploy a heterogeneous fleet; for the current study this would overly complicate both the representation of the model and the interpretation of the results. 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 discuss the costs of value-adding services. 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. The lower bounds are equivalent to 0.8 times the upper bounds. The bounds are generated randomly for each receiver.

Based on confidential price data provided by the UCC expert, we set representative price ranges for the UCC. Receivers always pay a monthly fee for the base service of the UCC (i.e., bundled deliveries); the expert indicates that this fee is typically independent of receiver location and delivery volumes. We set the price range for the base service for receivers at €60-70 per month. Carriers using the UCC pay per outsourced delivery stop. The corresponding price range is set at €12-18 per stop. Finally, we set the profit margin on value-added services at 20% (i.e., the price is 125% of the costs).

4.2.5. Municipality properties

Aside from implementing regulations, the main design choice for the municipality is how to distribute subsidies. Subsidies might be based on, e.g., the forwarded volume, the number of trucks, or time elapsed. 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 municipality 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. Subsidy schemes are terminated after 2 years.

4.3. 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. Variable B only has two levels. The variable levels are shown in Table 5; each unique combination of variables represents a scheme. We apply a full factorial design, resulting in $2^1 \cdot 3^6 = 1,458$ schemes to evaluate. For some variables that are particularly prone to

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

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

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 €/m³	7–20 €/m³	26–56 €/m³
G	Margin value-adding services	0%	20%	33.3%

change (based on preliminary tests), we perform additional sensitivity analysis in Section 5.2.

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 conceivable in the context of urban freight logistics within Denmark, either currently or in the near future.

We start by describing the administrative measures; in both cases the UCC is exempted. Copenhagen currently allows vehicles to deliver in the medieval center only between 9.00 and 11.00am. Our first test variable (A) therefore relates to the adjustment of this access time restriction. We test two alternatives, namely setting the window between 7.00 and 9.00 (requiring receivers to commit extra personnel hours for receiving goods) and omitting the access time window (potentially enabling carriers to reduce the required number of trucks). Test variable (B) refers to the zone-access fee for trucks; which in the current system is negligible for frequently visiting trucks and therefore set to 0. As alternative value we use €7 per visit; the city has used the same fee for certain vehicles back in 2002 (OECD, 2003).

Next, we discuss the subsidy measures that we test. Although the municipality expert indicated that the willingness to subsidize UCC initiatives is currently low, *Citylogistik-kbh* has received public funding in the recent past (Gammelgaard, 2015). In our experiments, we assume a two-year subsidy period; after this period *Citylogistik-kbh* went private as well. Subsidies might also be awarded to receivers or carriers for utilizing the UCC. Subsidizing carriers (variable C) or receivers (variable D) might generate initial commitment from these parties and lower the operating costs of the UCC. 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. Variable F sets three cost ranges that each represent lower and upper bounds for the handling costs, with the handling costs per m³ decreasing linearly with the increase in volume handled (see Section 3.2). Finally, variable G tests the impact of the profit margin that the UCC makes on value-adding services; we test profit margins of 0%, 20%, and 33.3%.

5. Results

In this section, we present the results of our simulation experiments. First, we address the financial and environmental performance of the individual agents in Section 5.1. We perform sensitivity analysis on several variables in Section 5.2.

Each simulation run represents a time period of 5 years. Subsidies may be awarded in the first 2 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 2 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 €/m³ (F_{II}) and a profit margin on value-adding services of 20% (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. Using the batch means method, we set the number of simulation runs per scheme at 10.

5.1. Performance

In this section, we discuss both the financial and environmental impact of various schemes, focusing on the generic insights obtained.

First, we discuss how the financial performance of each agent type is affected by adjusting the variable levels. Figure 2 shows the financial performance per agent type (excluding the municipality) for the tested schemes; to aid the visual presentation only every 7th data point are displayed and scenarios are sorted on UCC performance. A positive percentage implies an improvement on the financial KPIs, a negative percentage indicates a loss compared to the default scenario. 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 (only markers above the 100% line imply a profitable UCC), (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.
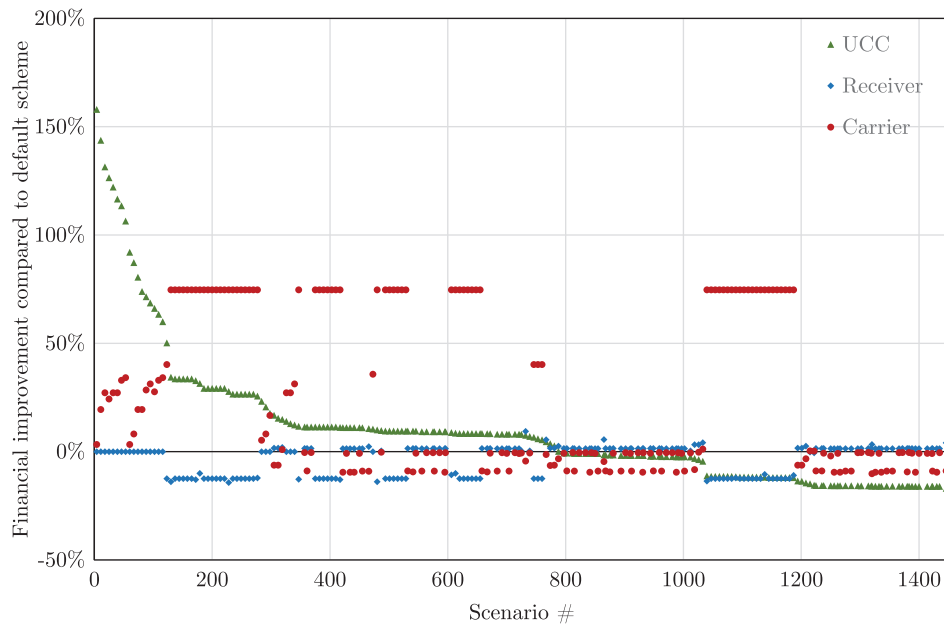
Figure 2. Financial performance, segregated per agent type for all scenarios. Performance is relative to the default scenario (represented by the 0% line); positive percentages indicate an improvement.

Table 6. Financial impact per variable level, segregated per agent type (receiver, carrier, UCC).

Variable level	Isolated effect			Main effect			Worst-case effect			Best-case effect		
	Rec.	Car.	UCC	Rec.	Car.	UCC	Rec.	Car.	UCC	Rec.	Car.	UCC
AI	−14%	75%	9%	−14%	72%	−49%	−25%	35%	−1245%	−10%	78%	25%
AIII	0%	−2%	−3%	0%	−3%	−41%	−3%	−55%	−1129%	5%	17%	5%
BIII	0%	−5%	−4%	0%	−6%	14%	−11%	−136%	−4%	4%	35%	563%
CII	1%	−1%	−2%	0%	3%	4%	−9%	−4%	−2%	2%	40%	122%
CIII	1%	−1%	−2%	1%	8%	24%	−9%	−136%	−2%	2%	37%	163%
DII	6%	−5%	−2%	0%	0%	−1%	−4%	−8%	−50%	6%	8%	38%
DIII	3%	−3%	0%	0%	1%	−3%	−6%	−5%	−75%	7%	12%	38%
EII	3%	0%	−3%	0%	3%	4%	−10%	−3%	−3%	4%	37%	129%
EIII	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%

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).

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.

Table 6 shows the impact of changing each variable on the financial KPIs of carriers, receivers, and the UCC, with positive signs indicating performance improvement. For each alternative variable level, we show its isolated effect (changing only a single variable level and setting all other variable levels at default), main effect (the average difference between all pairs of equivalent schemes, with a single variable level altered in one of the pairs), worst-case effect (the largest negative effect from the pairs of schemes), and best-case effect (the largest positive effect from the pairs of schemes).

We proceed to reflect on the influence of each variable. Shifting time windows (A_I) is a very effective measure to commit receivers to the UCC as it allows receivers to pay extra receiving costs. However, as a result carriers have no need to pay the UCC, which typically translates to insufficient 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 ($C_{II}, C_{III}, D_{II}, D_{III}, E_{II}, E_{III}$). Subsidizing carriers or the UCC yields positive effects, yet subsidizing carriers appears more efficient. Subsidizing receivers has little effect. All subsidy measures have a limited impact as a stand-alone measure; they must be combined with other measures to achieve a sustainable state after the subsidy period ends.

Adjusting the estimated handling costs at the UCC (F_I and F_{III}) has a strong impact on the financial performance of the UCC; we found no sustainable schemes for the high-cost setting. Finally, varying the profit margin on value-

adding services (G_I and G_{III}) has an impact on the net income of the UCC, yet the overall impact is relatively small as income from value-adding services is only about 15%.

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.

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 3 shows the income and costs for the UCC over time for a scheme that

focuses on attracting carriers before receivers, Figure 4 shows the same information for a scheme that aims to attract receivers first. The scheme that aims to first commit carriers performs notably better. Although the receiver-oriented scheme attracts more users overall, the UCC obtains its revenue solely from the receivers. In the carrier-oriented 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.

We try to identify schemes that yield a positive net result for the UCC without decreasing the financial performance of the other agents, thereby providing a rational base for long-term sustainability. Figure 5 shows the financial KPIs for the best scheme—in terms of UCC profitability—compared to the performance under the default scheme. Despite

Figure 3. Financial performance for the UCC under a scheme that primarily aims to attract carriers, using the settings A_{II}, B_I, C_I, D_I, E_I, F_I, G_{II}.
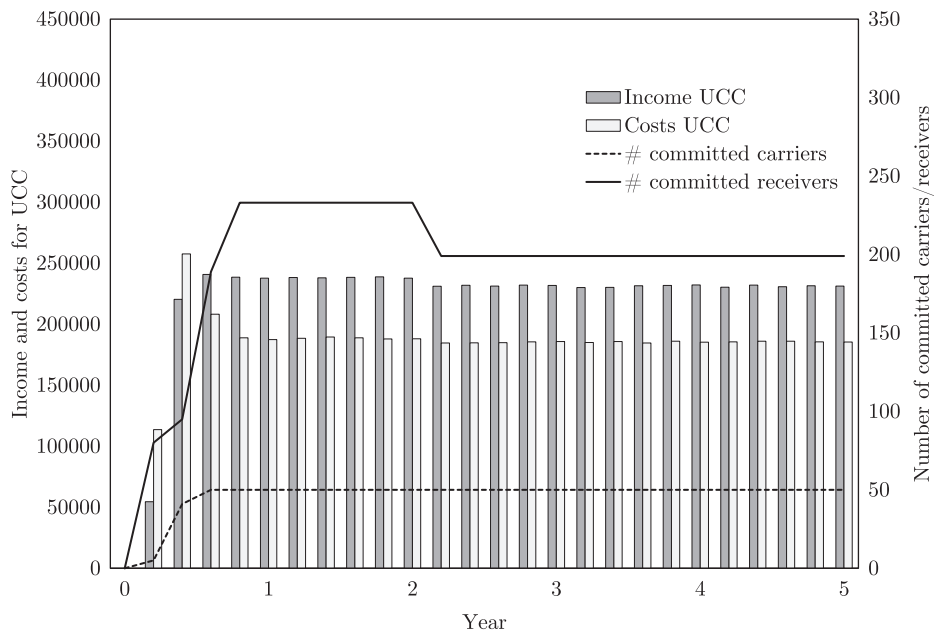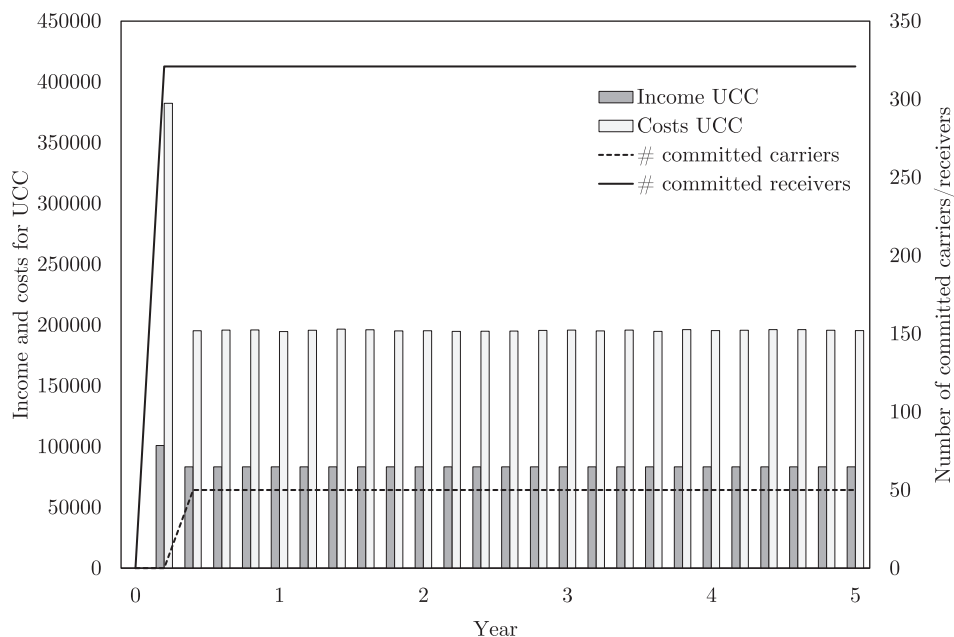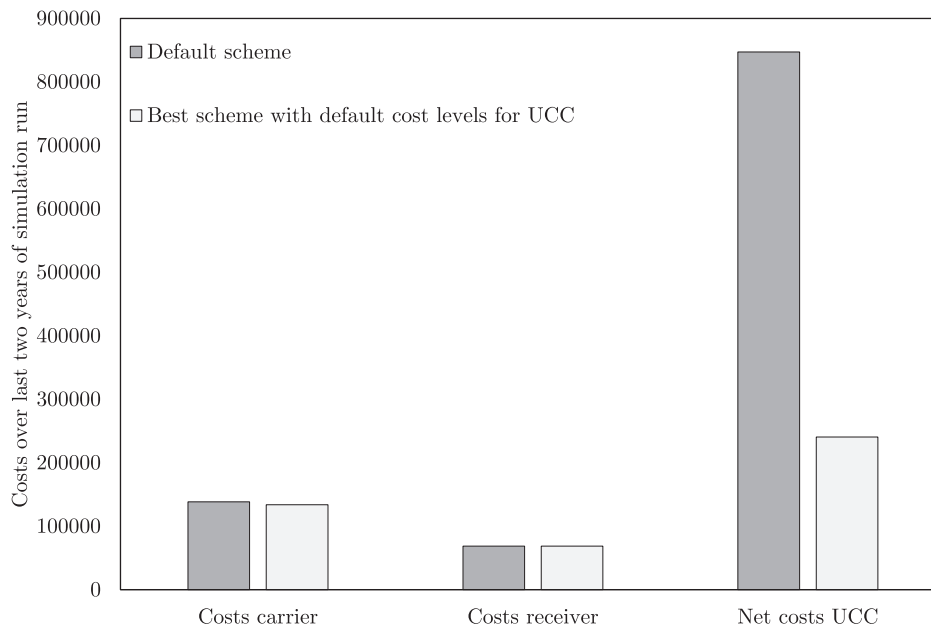

Figure 4. Financial performance for the UCC under a scheme that primarily aims to attract receivers, using the settings A_{II}, B_I, C_I, D_I, E_I, F_I, G_{II}.

Figure 5. Financial performance of carriers, receivers, and UCC under both the default scheme (A_{II}, B_I, C_I, D_I, E_I, F_{II}, G_{II}) and the financially best-performing scheme (A_{II}, B_{II}, C_{III}, D_I, E_{III}, F_{II}, G_{II}).

being the best-performing scheme under average cost settings (F_{II} and G_{II}), it still yields a loss of 8.5% to the UCC. The scheme is characterized by 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. It results in a cost reduction for the carriers, virtually no cost change for the receivers, and a major reduction in net costs for the UCC. In Section 5.2 we fine-tune several variables of the best scheme to verify whether profits are attainable under average cost settings for the UCC.

We proceed to reflect on the relation between financial and environmental performance. From an environmental perspective, all schemes perform better than in the scenario without a UCC. Compared to the default scenario, for the less-than-truckload flows modeled in the simulation, the best schemes reduce emissions by approximately 70%, 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%. These considerable benefits indicate that the concept of a UCC makes sense from an environmental perspective.

Table 7 compares the environmental KPIs for the financially best-performing scheme (see Figure 5) 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%.

5.2. Sensitivity analysis

We perform sensitivity analysis on variables that are both subject to considerable variability and are expected (based on preliminary tests) to have a significant impact on the results, namely (i) the zone-access fee, (ii) the width of the access time windows, (iii) the carrier subsidy level, (iv) the UCC price for carriers, (v) the division between centralized and decentralized receivers, and (vi) the size of the retailer target group. We simulate with multiple numerical values for each variable of interest, while keeping all other variables at their default levels. Furthermore, we fine-tune several variables in the financially best-performing scheme, as this scheme—under average cost settings—yields financial losses for the UCC.

We test zone-access fees in the range $\{0, 2, ..., 20\}$. We find that under the default scheme, a fee of €12 is the tipping point that spurs carriers to use the UCC. A fee of €18 or higher is needed for a profitable UCC. Although such fees are likely too high for practical applications, this analysis indicates that tweaking the entrance fee may have a substantial impact on the performance of a scheme.

The access time restriction of two hours that is currently applied in the city of Copenhagen appears ineffective to persuade carriers to use the UCC. We test the impact of time access window in the width range $\{0.5, 1, ..., 5\}$ on the number of carriers that commit to the UCC. Windows with a width up until one hour have the intended effect; for wider

Table 7. Performance on environmental KPIs compared between the default scheme and the financially best-performing scheme.

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%
No. of small trucks	2,937	11,493	+291%
No. of large trucks	26,244	0	−100%
Total no. of trucks	29,181	11,493	−61%
Distance small trucks ($\times 1000$ km)	38	139	+261%
Distance large trucks ($\times 1000$ km)	385	0	−100%
Total distance trucks ($\times 1000$ km)	423	139	−67%

All outcomes correspond to the final 2 years of the simulation.

windows the number of committed carriers drops. Windows wider than two hours do not aid in attracting carriers to utilize the UCC, unless combined with other measures.

Attracting carriers as quickly as possible improves the long-term financial sustainability of the UCC. We aim to find the smallest subsidy amount that the municipality needs to spend in order to commit carriers within a certain subsidy period. We test 10 different subsidy levels—ranging from 2% to 20%—and their effects on the commitment of carriers over time, measured during the two-year subsidy period. 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 2 years. To attract higher numbers of carriers directly at the start, a level of about 30% is required.

Because carriers are very price-sensitive, we test 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, we now 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.

For the ratio between centralized and decentralized receiver profiles, we test ratios 100/0, 75/25, 50/50/25/50, and 0/100. We observe that decentralized profiles are more likely to use the UCC (147 out of 321 receivers when all have decentralized profiles, compared to 0 when all have centralized profiles), leading to higher UCC incomes. Under the default scheme the UCC remains financially unsustainable. When performing the same sensitivity analysis on the best scheme, a higher share of decentralized profiles yields profitable scenarios. Thus, profitability of the UCC with a target group composed of relatively many decentralized profiles appears more likely.

To test the sensitivity to the size of the target group, we take 10%, 20%, 30%, 40%, and 50% of the 1071 receivers and scale the number of carriers correspondingly. We compare the relative losses and profits to verify whether the size of the target group affects profitability, both for the default scheme and the best scheme. For the default scheme the impact is limited, although relative UCC losses decrease when increasing the target group size. For the best scheme, target groups larger than 30% actually yield profits for the UCC (up to 7.7%), whereas smaller target groups result in losses up to 31.5%.

We conclude this section with an evaluation of the impact of fine-tuning the best-performing scheme (see Figure 5), as a loss of 8.5% renders the UCC insolvent in the long term. We highlight the adjustments that result in UCC profits. Increasing subsidy levels for either the UCC or the carriers from 20% to 30% instantly commits almost all carriers from the start, resulting in a profit of 12.1% for the UCC. Lowering the price of the base service from €60–70 to €40–50 results in 15% more receivers in the steady state and pushes the profit margin of the UCC to 2.2%. Finally,

raising the zone-access fee from €7 to €9 yields a profit of 0.3% for the UCC. These results show that relatively small price changes may considerably impact the profitability of the UCC.

6. Conclusions

In this study we tested 1,458 different schemes, for which we measured both financial and environmental KPIs. Considerable environmental improvements may be achieved through the use of a UCC, reducing truck kilometers driven in the city by about 65% and reducing emissions by about 70%. The key challenge is to find schemes that are also financially sustainable. The UCC is able to obtain the highest revenues by first convincing carriers to outsource their stops and subsequently selling value-adding services to the receivers in the city. Adopting a strictly financial perspective for decision-making (thus not monetizing environmental costs), the concept of a UCC appears to be unsuccessful without supporting measures. Temporary subsidies to the carriers and imposing a zone-access fee are the most effective measures in achieving a steady state in which the UCC is profitable and may operate without external funding after reaching a certain scale of operations. We do stress, however, that also in our simulation achieving financial stability is highly challenging and even unattainable for certain cost settings. Although several schemes show that the UCC may ultimately survive without subsidies, we do not claim that this is attainable for all UCCs in practice; both the user base and the operational costs are crucial in this regard.

The obtained insights correspond to recent findings in literature; see, e.g., Kim et al. (2015) and Van Duin et al. (2016) for insights comparable to ours. In particular, the importance of supporting regulation, the focus on carriers as the main source of income, and the need to reach sufficiently high throughput within limited time are common themes in literature. Although the importance of regulation in general has been validated, the effectiveness of individual administrative policies and their combinations cannot be sufficiently verified based on existing literature.

We discuss the impact of the two most important deviations from practice of our simulation model. First, the sequence in which carriers and receivers commit to the UCC in our model is crucial. 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. In practice decisions are made more gradually; the main takeaway remains that the focus must be on attracting carriers first and that administrative measures should support this approach. A second deviation from practice is that the simulated UCC adopts volume-dependent price ranges. Although the underlying argument of economies of scale holds for the operating costs, in practice the continuous price changes might confuse users and require frequent contract renegotiations. The main reason for using ranges rather than fixed price levels is to identify steady states more easily. As fixed

price levels may only work for a specific scheme, it is difficult to make generic statements regarding single price levels.

General limitations of our work are the lack of data for some properties—necessitating several strong assumptions, particularly regarding the cost structure of the UCC and the order patterns of potential UCC users—and the small number of experts consulted. Although we have made the effort to cross-check data with our expert interviews and take into account practical points of view as much as possible, additional data sources and expert interviews might aid in validating and extending the findings presented in this paper.

We conclude this paper with the key managerial insights obtained from the experiments.

- The commitment of carriers to the UCC should be ensured before targeting the receivers.
- Subsidies are most effectively allocated to the carriers.
- Access time restrictions only aid the UCC if the access window is set sufficiently narrow.
- Setting access time restrictions before the opening times of stores is an effective measure to generate commitment from receivers.
- Zone-access fees can have a positive effect in combination with other measures.

Acknowledgment

Funding

ORCID

Wouter van Heeswijk 🆔 http://orcid.org/0000-0002-5413-9660
Rune Larsen 🆔 http://orcid.org/0000-0002-2451-1177
Allan Larsen 🆔 http://orcid.org/0000-0002-6647-6832

References

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

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

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

Anand, N., Meijer, D., Van Duin, J., Tavasszy, L., & Meijer, S. (2016). Validation of an agent based model using a participatory simulation gaming approach: The case of city logistics. *Transportation Research Part C: Emerging Technologies*, 71, 489–499.

Bektaş, T., Crainic, T. G., & Van Woensel, T. (2017). From managing urban freight to smart city logistics networks. In Konstantinos Gakis and Panos Pardalos (Eds.), *Network Design and Optimization for Smart Cities.* (pp. 143–188). Singapore: World Scientific.

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

Bohne, S., Ruesch, M., & Leonardi, J. (2015). *Best practice handbook 3*.

Browne, M., Allen, J., & Woodburn, A. (2007). *Evaluating the potential for urban consolidation centres*.

Browne, M., Sweet, M., Woodburn, A., & Allen, J. (2005). Urban freight consolidation centres. *Transport Studies Group*, 10, 1–185.

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

Crainic, T. G. (2012). Long-haul freight transportation. In Hall, R. W. (Ed.), *Handbook of Transportation Science* (pp. 433–492). New York, NY: Springer Science.

Crainic, T. G., Ricciardi, N., & 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. (Eds.), *City distribution and urban freight transport: Multiple perspectives* (pp. 37–56). Cheltenham: Edward Elger.

de Assis Correia, V., de Oliveira, L. K., & Guerra, A. L. (2012). Economical and environmental analysis of an urban consolidation center for Belo Horizonte city (brazil). In Taniguchi, E. and G, T. R. (Eds.), *Procedia—Social and Behavioral Sciences* (Vol. 39, pp. 770–782). Seventh International Conference on City Logistics which was held on June 7–9, 2011; Mallorca, Spain.

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

Hemmelmayr, V. C., Cordeau, J.-F., & Crainic, T. G. (2012). An adaptive large neighborhood search heuristic for two-echelon vehicle routing problems arising in city logistics. *Computers & Operations Research*, 39(12), 3215–3228.

Holguín-Veras, J. (2008). Necessary conditions for off-hour deliveries and the effectiveness of urban freight road pricing and alternative financial policies in competitive markets. *Transportation Research Part A: Policy and Practice*, 42(2), 392–413.

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

Jacyna, M. (2013). The role of the cargo consolidation center in urban logistics system. *International Journal of Sustainable Development and Planning*, 8(1), 100–113.

Kim, G., Ong, Y.-S., Heng, C. K., Tan, P. S., & Zhang, N. A. (2015). City vehicle routing problem (city VRP): A review. *IEEE Transactions on Intelligent Transportation Systems*, 16(4), 1654–1666.

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

Le Pira, M., Inturri, G., Ignaccolo, M., Pluchino, A., & Rapisarda, A. (2017). Finding shared decisions in stakeholder networks: An agent-based approach. *Physica A: Statistical Mechanics and Its Applications*, 466, 277–287.

Lebeau, P., Verlinde, S., Macharis, C., & Van Mierlo, J. (2017). How can authorities support urban consolidation centres? A review of the accompanying measures. *Journal of Urbanism: International Research on Placemaking and Urban Sustainability*, 10(4), 468–486.

Luxen, D., & 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* (pp. 513–516). New York, NY: ACM.

Malhene, N., Trentini, A., Marques, G., & Burlat, P. (2012). Freight consolidation centers for urban logistics solutions: The key role of interoperability. In *Digital Ecosystems Technologies (DEST), 2012 6th IEEE International Conference on* (pp. 1–6). IEEE.

Marcucci, E., & Danielis, R. (2008). The potential demand for a urban freight consolidation centre. *Transportation*, 35(2), 269–284.

Marcucci, E., & Gatta, V. (2017). Investigating the potential for off-hour deliveries in the city of Rome: Retailers perceptions and stated reactions. *Transportation Research Part A: Policy and Practice*, *102*, 142–156.

Marcucci, E., Le Pira, M., Gatta, V., Inturri, G., Ignaccolo, M., & Pluchino, A. (2017). Simulating participatory urban freight transport policy-making: Accounting for heterogeneous stakeholders preferences and interaction effects. *Transportation Research Part E: Logistics and Transportation Review*, *103*, 69–86.

Nordtømme, M. E., Bjerkan, K. Y., & Sund, A. B. (2015). Barriers to urban freight policy implementation: The case of urban consolidation center in Oslo. *Transport Policy*, *44*, 179–186.

OECD (2003). *Delivering the goods: 21st century challenges to urban goods transport*. Paris: OECD.

O'Rourke, D. (2014). The science of sustainable supply chains. *Science*, *344*(6188), 1124–1127.

OSM Foundation (2017). *OpenStreetMap*. Retrieved from 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., & 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., & 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., & 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., & Monigl, J. (2006). Quantification of urban freight transport effects I. *BESTUFS Consortium*, www.bestufs.net.

Tamagawa, D., Taniguchi, E., & 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., & 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. (Eds.), *Urban transportation and logistics: Health, safety, and security concerns (pp. 1–30)*. Boca Raton, FL: CRC Press.

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

Triantafyllou, M., Cherrett, T., & Browne, M. (2014). Urban freight consolidation centers: Case study in the UK retail sector. *Transportation Research Record: Journal of the Transportation Research Board*, (2411(1), 34–44.

United Nations (2014). Worlds population increasingly urban with more than half living in urban areas. Retrieved from 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., & 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 Dam, T., Wiegmans, B., & Tavasszy, L. A. (2016). Understanding financial viability of urban consolidation centres: Regent Street (London), Bristol/Bath & Nijmegen. *Transportation Research Procedia*, *16*, 61–80.

van Duin, J. H. R., van Kolck, A., Anand, N., Tavasszy, LóA., & 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., & 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., & 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., & 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., & Qureshi, A. G. (2014). Multi-agent systems modelling for evaluating joint delivery systems. *Procedia-Social and Behavioral Sciences*, *125*, 472–483.