Exploring conditions for economic sustainability of city hubs adoption in urban logistics - a system dynamics approach

Taylor & Francis
Taylor & Francis Group

International Journal of Sustainable Transportation

ISSN: 1556-8318 (Print) 1556-8334 (Online) Journal homepage: www.tandfonline.com/journals/ujst20

Exploring conditions for economic sustainability of city hubs adoption in urban logistics - a system dynamics approach

Claudia Andruetto, Giovanni Zenezini, Henrik Gillström & Anna Pernestål

INTERNATIONAL JOURNAL OF SUSTAINABLE TRANSPORTATION
https://doi.org/10.1080/15568318.2025.2584181

Exploring conditions for economic sustainability of city hubs adoption in urban logistics - a system dynamics approach

Claudia Andruetto[a], Giovanni Zenezini[b], Henrik Gillström[c], and Anna Pernestål[a]

[a]Integrated Transport Research Lab, KTH Royal Institute of Technology, Stockholm, Sweden; [b]Department of Management and Production Engineering, Politecnico di Torino, Turin, Italy; [c]Department of Management and Engineering, Linköpings Universitet, Linköping, Sweden

ABSTRACT
Transport-related externalities have a negative impact on urban environments and health. Therefore, urban logistic systems encounter significant sustainability challenges. One urban transport strategy is city hubs, which can achieve a more effective system. However, city hubs have yet to realize their full potential due to the challenges of their implementation. This paper investigates the dynamics of city hub implementation from the perspectives of the Logistic Service Providers (LSPs), the hub operator and the receivers of the goods. Drawing from qualitative and quantitative insights from a case study in Stockholm, a system dynamics model is built to understand these dynamics. The results of this model demonstrate that the city hub is economically sustainable only if collaboration is achieved between LSPs and receivers. However, the total system cost increases with collaboration. When collaboration cannot be achieved, the public sector's involvement is crucial to achieving hub adoption. The results also show that implementing an environmental zone (internal combustion engine vehicles are forbidden entry) does not help hub adoption, as the share of the LSPs cost spent on vehicles is low compared to other costs. Therefore, policies favoring the actors involved in the scheme should be considered. The main contribution of this paper lies in identifying possible strategies and outcomes of city hub implementation within the studied area and providing guidance for policymakers on policies for successful implementation. Moreover, the model can be adapted to other case studies by adjusting the input data, thereby serving as a tool for policymakers in different geographical contexts.

ARTICLE HISTORY
Received 11 June 2024
Revised 9 October 2025
Accepted 13 October 2025

KEYWORDS
City hubs; economical sustainability; sustainable urban logistics; system dynamics modeling; urban logistics policies;

1. Introduction

Urban logistic systems encounter significant challenges regarding sustainability. Transport-related externalities (i.e., greenhouse gas emissions, congestion, pollution, and noise) have a negative impact on urban environments and public health (Ranieri et al., 2018). Furthermore, the expected increase in e-commerce and circular economy (Bosona, 2020; Nenni et al., 2019; Sheth et al., 2019) suggest a surge in last mile transport needs, potentially exacerbating these transport-related externalities (Ranieri et al., 2018). The context of this paper is an area in the city center of Stockholm where the implementation of a zero-emission zone is planned. The city of Stockholm aims to achieve fossil-free transport solutions and congestion reduction by 2040 through increased efficiency and coordination (Stockholms stad, 2020). To reach these goals and mitigate transport-related externalities, various logistics innovations such as electric trucks, cargo bikes, and consolidation centers are under development and implementation (MDS, 2012). However, policymakers require more insights into the impacts of these innovations to make informed decisions and design policies leading to a more sustainable system (Lindholm and Behrends, 2012; McLeod and Curtis, 2020).

One such urban transport strategy which frequently appears in the urban logistics literature is urban consolidation centers or city hubs, as these can reduce the transport-related externalities by achieving a more effective system (Duin et al., 2018; Nataraj et al., 2019). According to Browne et al. (2005), there are different applications of city hubs: in this paper, we focus on a hub where flows directed to the same urban area, i.e., the a part of the city center of Stockholm, are consolidated. Implementing city hubs can reduce the distance traveled and boost fleet efficiency, thereby mitigating pollution and congestion (Nataraj et al., 2019; Nathanail et al., 2020; Nocera and Cavallaro, 2017; Rabe et al., 2018). However, their implementation faces two primary challenges: the competitive nature of the logistics market and the lack of functioning business models for the hub operator (Akgün et al., 2020; Heeswijk et al., 2019; Nataraj et al., 2019; Paddeu et al., 2018).

Despite their frequent mention in the urban logistics literature, city hubs have yet to realize their full potential due

CONTACT Claudia Andruetto claudiandruetto@gmail.com Integrated Transport Research Lab, KTH Royal Institute of Technology, Drottning Kristinas väg 40, 114 28 Stockholm, Sweden.

to the challenges of their implementation, which are mainly economical. Understanding why city hubs falter and identifying strategies and policies to facilitate their adoption remains a gap in the literature, particularly looking at the problem including different actors' perspectives. Therefore, this paper investigates the dynamics of city hub implementation from the perspectives of the central actors in the system, i.e., the Logistic Service Providers (LSPs), the hub operator, and the receivers of the goods. These dynamics are also influenced by the conditions of the specific urban logistic system studied, such as pricing models, demand structures and types of actors involved in the studied system. Drawing from the qualitative insights in existing literature, this research aims to quantitatively model the behavior of these actors and assess how different policies and strategies could influence city hub implementation. A system dynamics approach to a case study in Stockholm is employed to achieve this objective. This method allows us to understand the dynamics of the problem and model the adoption of the hub service from the different actors' perspectives. The resulting quantitative model addresses the following research questions: (i) under what conditions are city hubs economically sustainable for all actors involved? and (ii) how do different strategies and policies impact the adoption of city hubs?

This paper contributes to the literature with a system dynamics model that aims to be adaptable to other case studies where city hubs are introduced, thereby serving as a tool for analyzing similar problems in different geographical contexts. Using the model can then help identify possible strategies and outcomes of city hub implementation and provide guidance for policymakers on viable policies for successful implementation. The remainder of the paper is organized as follows: Section 2 provides a background on city hubs and system dynamics in urban logistics, Sections 3 and 4 give an overview of the method and the description of the model, Section 5 presents the results of the scenarios and sensitivity analysis, Section 6 discusses these results and Section 7 provides concluding remarks.

2. Literature review

This section presents a short review of the literature of city hubs and consolidation as urban practice and of the use of system dynamics modeling in the urban logistics field.

2.1. City hubs and consolidation

A city hub (also called an urban consolidation center) is a urban logistics practice that functions as a decoupling point between outbound and inbound freight flows, where goods from different LSPs are consolidated at the hub and thereafter transported to the receivers in the city (Browne et al., 2005; van Rooijen and Quak, 2010). Most of the research focuses on business-to-business receivers, such as retail stores, offices, restaurants, and other types of establishments that receive deliveries (Browne et al., 2005; Veličković et al., 2018). Through consolidation, city hubs can enable higher fill rates and thus improved efficiency of deliveries which lead to decrease in total vehicle kilometer traveled in the city (Johansson and Björklund, 2017; Kin et al., 2018). Furthermore, due to the short delivery distances, the city hub enables a shift to more environmentally friendly vehicle that are suited for urban deliveries, including smaller freight vehicles (van Rooijen and Quak, 2010) or electric vehicles (Paddeu, 2021). Thus, implementing city hubs can have great benefits for cities and the inhabitants, e.g., reduced emissions (Katsela et al., 2022; Paddeu, 2021).

Besides the potential benefits that affect cities and society in large, city hub implementation especially affect two types of actors, namely LSPs and receivers. The main benefits for LSPs for using the hub service is that they can avoid entering congested cities and therefore improve their efficiency (Katsela et al., 2022) and potentially reduce their cost. Previous research (e.g., Paddeu, 2021) found that dwell time, in terms of time spent in traffic queues or waiting at unloading docks as problematic and something that affect the overall efficiency. The downsides related to the use of the city hubs include losing contact with their customers, reduced driving assignments, and loss of control over the freight flow (Browne et al., 2007), low willingness for receivers to participate in hub schemes (Johansson and Björklund, 2017), and the need for receivers to pay for the hub service (Heeswijk et al., 2019). These downsides have previously been identified as barriers that affect LSPs' willingness to use city hubs, and together with the difficulty of achieving financial viability, have been the main reasons for the low long-term success of city hubs (Björklund and Johansson, 2018; Browne et al., 2007). For the receivers, there are several potential benefits of using the transport service for the hub and the goods are consolidated (Gammelgaard et al., 2016). The use of city hubs will, for example, limit the number of deliveries to each receiver, which results in fewer interruptions for the personnel in reception occasion, more packages per delivery (Gammelgaard et al., 2016; Johansson and Björklund, 2017). On the other hand, it can also lead to longer time spend for each delivery occasion and risk of longer lead times due to the extra transshipment point and something that recipients must consider (Browne et al., 2005).

As the city hub scheme has been proven to have several downsides, the policy perspective is critical to supporting city hub implementation and adoption. The public sector can introduce policies or restrictions, which have been studied by, amongst others (Akgün et al. 2020; Anand et al. 2021; Heeswijk et al. 2019; Holguín-Veras et al., 2020a). Anand et al. (2021) describe a delivery cap and price policy combined with a subsidy for a city hub alternative to reduce carbon emissions for urban goods delivery. The policy is practically implemented using carbon credit points, inspired by the emission trading mechanism of the Kyoto Protocol. Anand et al. (2021) test the policy using an agent-based model in the inner city of Rotterdam. Their simulation results show that this policy could positively influence the use of city hubs, ensuring financial viability. Moreover, Heeswijk et al. (2019) mention policies such as access time restrictions and zone-access fees. Low emission zones could also influence city hubs, as they are zones with restricted access to reduce pollution levels, together with time access restrictions, which impose restrictions on the times freight vehicles can enter a specific area (Holguín-Veras et al., 2020b). The city hubs could take advantage of such restrictions: for example, the use of clean vehicles in the urban consolidation centers in Norway enables them to take advantage of priority lane policies (Holguín-Veras et al., 2020a). However, the previous literature does not focus on understanding unintended consequences of these policy on a system-level.

Furthermore, Akgün et al. (2020) suggests that the public sector should provide strong support even after the startup phase by forcing LSPs to use the city hubs. One way is to apply traffic restrictions to all LSPs except city hub users (Holguín-Veras et al., 2020a). An example of such an approach is the CityPorto Padova, where only the city hub vans are allowed to use the dedicated lanes of buses and taxis and have no time windows for loading/unloading in the ZTL (Limited Traffic Zone) (Leonardi et al., 2014). Another approach that is highlighted by Holguín-Veras et al. (2020a) is receiver-lead consolidation. In these cases, receivers either ask suppliers to combine their deliveries and make consolidated shipments, or change their address to a separate facility (Holguín-Veras et al., 2020a).

The literature review on city hubs and consolidation strategies underlines that understanding why city hubs falter remains a gap. The system dynamics methodology can help address this gap from a dynamic and system-level perspective, particularly looking at the problem including different actors' perspectives and their adoption dynamics. Moreover, it can help by identifying relevant strategies and policies to facilitate their adoption, together with potential unintended consequences of these policies on a system-level.

2.2. System dynamics in urban logistics

System Dynamics models have been established within the domain of urban logistics only in recent years, beginning with a seminal study by Kunze et al. (2016) who provided a first, qualitative, understanding on the mutual influence of the main decisions taken by urban logistics actors. Their work paved the way for quantitative SD models to represent the dynamics of the urban logistics system over time. The first quantitative SD model of such was then introduced by Thaller et al. (2016) to encompass several key elements of urban logistics such as population-driven goods demand, freight trip demands for transport operators, road mileage, fuel consumption, transport lead time, and associated costs. While the scope of this model was general, other studies have attempted to apply the SD methodology to specific urban logistics innovations or issues. At least three system dynamics models for Underground Logistics Systems (ULS) have been published in the last 4 years (Dong et al., 2019; Hu et al., 2022; Xu et al., 2022). Dong et al. (2019) studied the impact of such initiative by linking freight demand to socioeconomic variables (e.g., GDP per capita) and grounding the capacity of the ULS to the availability of economic resources of the urban logistics regulator. These resources are affected by the negative externalities of urban logistics which the ULS attempts at reducing, thus engendering the reinforcing loop around which the SD model is built. Hu et al. (2022) proposed a hybrid System Dynamics - Agent-based model within the boundaries of the city of Beijing. The causal loop are here embedded within the main agents, namely customers (e.g., Logistics Service Providers (LSP) and retail chains), ULS operator and the government.

Three main subsystems are identified in this paper: (i) a demand-market subsystem whereby demand and willingness to pay by the LSP are calculated; (ii) a subsystem where the pricing by the ULS operator is optimized; (iii) a subsystem where externalities are estimated. Lastly, Xu et al. (2022) focused their System Dynamic model on the interconnections between the characteristics of ULS and the outbreak of the Covid-19 pandemic in Wuhan, China. Here, the alternative solution represented by the ULS competes with the traditional freight vehicle transportation, increasing the efficiency and safety of the delivery process, thus increasing the demand of the ULS. Furthermore, a reinforcing loop is created when this demand increase engenders a reduction in the unit costs. A similar approach is used by Hu et al. (2020) to analyze the development of urban rail freight transportation systems (URFT). It can be noted from this brief literature review that one of the main leverages for the success of urban logistics initiatives is the service pricing, which can be treated as an endogenous variable proportional to the operating costs. These are in turn affected by economies of scale, which are driven by the volume and capacity of the infrastructure. Furthermore, in all of the previous models government subsidies are included in reinforcing loops as leverage for the attractiveness of urban logistics solutions. To the best of our knowledge, only Melkonyan et al. (2020) has applied a System dynamics methodology to study a wholly market-based urban logistics system, modeling three alternative last-mile distribution strategies for a food delivery service. Their model is centered around economic, technological, environmental and social variables.

To summarize, the understanding of why city hubs falter and identifying strategies and policies to facilitate their adoption are gaps in the existing literature. Moreover, to the best of our knowledge, there are no applications of system dynamics to the problem of city hubs in urban logistics. Therefore, this paper addresses these gaps in the literature by applying the system dynamics methodology, further explained in the following section. The developed system dynamics model aims to identify possible strategies and outcomes of city hub implementation and provide guidance for policymakers on viable policies for successful implementation.

3. Methodology

Urban logistic systems are complex, influenced by multiple actors' decisions, with time delays and intricate cause-and-effect relationships. In this paper, the perspectives of three actors in the system are explored: the hub operator, the LSPs and the receivers. To understand the dynamics of city hub implementation, a system thinking approach was adopted (Sterman, 2001). Within the system thinking paradigm, system dynamics was used as a method to

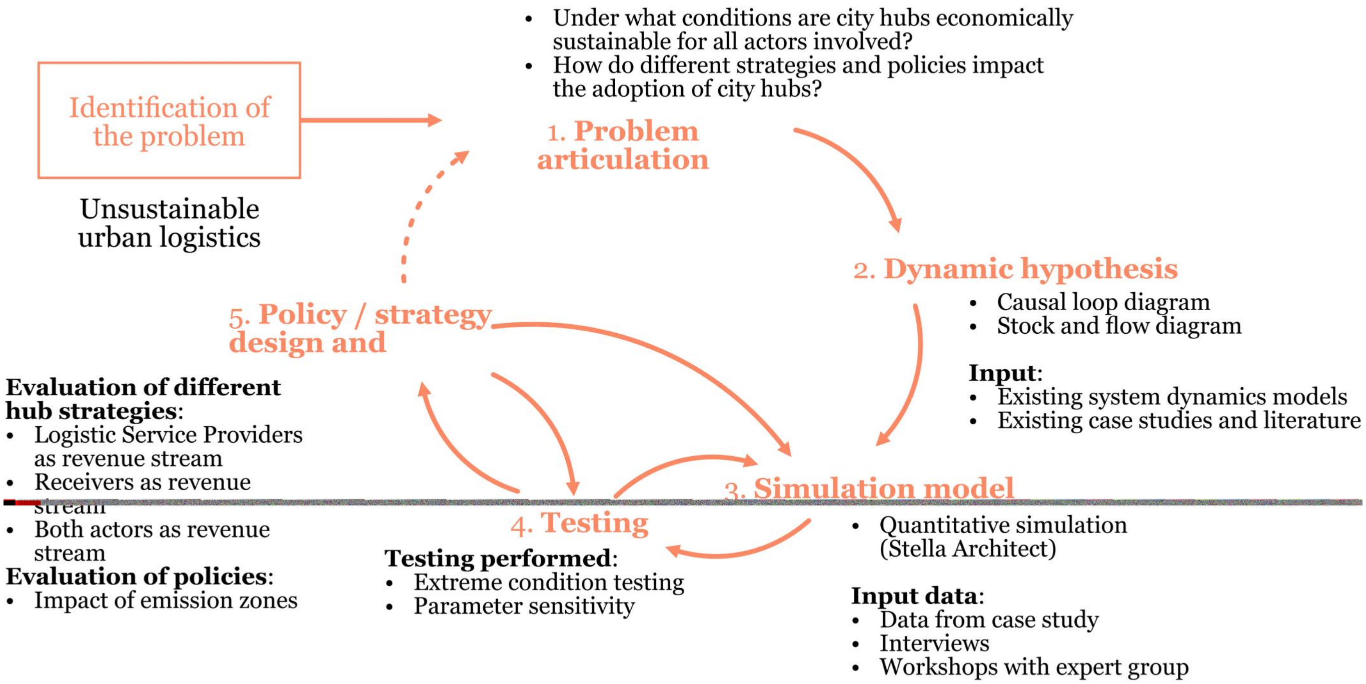

Figure 1. Methodology of the work. The figure shows the five steps of the system dynamics process, with arrows connecting each step. The dashed arrow connecting step five to step one indicates the possibility of going back to problem articulation after a modeling process has finished.

quantitatively model the system (Sterman, 2001). Figure 1 illustrates the methodology used in this study. Section 3.1 presents the system dynamics framework in detail, while Section 3.2 presents the specific case studied in this paper.

3.1. System dynamics framework

The methodology draws from Sterman (2000), who outlined five steps for employing the system dynamics method, shown in Figure 1. Once a problem has been identified, the first step is the problem articulation. Within this step, the research questions are identified. The research questions identified in this paper are: i) under what conditions are city hubs sustainable? and ii) how do different strategies and policies impact the sustainability of city hubs? These questions relate to the *unsustainable urban logistics* broader problem. Subsequently, a dynamic hypothesis is formulated (step 2), leveraging existing system dynamics models, case studies and literature. This second step involves the creation of Causal Loop Diagrams (CLDs) and stock and flow diagrams. The main steps presented in this work are the simulation model (step 3), the testing (step 4) and the policy design and evaluation (step 5).

The quantitative simulation model (step 3) was created starting from previous qualitative work carried out by the authors (Andruetto et al., 2024). Andruetto et al. (2024) identify main dynamics related to the barriers and potentials of city hubs implementation in Stockholm in a qualitative way. In this study, these dynamics are quantified and are studied from different actors' perspective, using input data from the case study (Section 3.2), interviews, and workshops with experts. Moreover, existing system dynamics models were used to consolidate its dynamics, and existing case studies and literature were used whenever data was not directly available. The model was created using the program Stella Architect version 3.2.1. The model simulation is configured to run over 120 months. Commencing from year 2023, the simulation progresses for 10 years until the year 2033. A time step of 1/4 (which corresponds to a weekly time step) has been selected for the simulation. The integration method employed is Euler.

Two types of testing were performed, extreme condition testing and parameter sensitivity (step 4), of which the results are elaborated in Section 5. The testing performed is described further Section 4.5. Finally, different hub strategies and policies were evaluated as scenarios using the model as a tool (step 5). The evaluated hub strategies are: LSPs as revenue stream (*LSP only* scenario), receivers as revenue stream (*receivers only* scenario), and both receivers and LSPs as revenue stream (*static cost* and *dynamic cost* scenarios). Moreover, an evaluation of the impact of the emission zone policy is also carried out. The results of these scenarios are presented in Section 5. These three last steps were iterated within the core modeling team, until relevant strategies and results were produced by the model. The input data were taken from a case study described below, interviews, and workshops with the expert groups. The expert groups included system dynamics researchers and logistic experts from academic, industrial and public sectors. Moreover, estimations and assumptions were made, based on the case study and on previous research. The limitations brought by these assumptions are discussed in section 6.4.

3.2. The Stockholm case study

The city center of Stockholm is an attractive geographical location for sustainable logistics innovation projects due to the strong commitment to addressing sustainability concerns. The City of Stockholm is planning to introduce an environmental

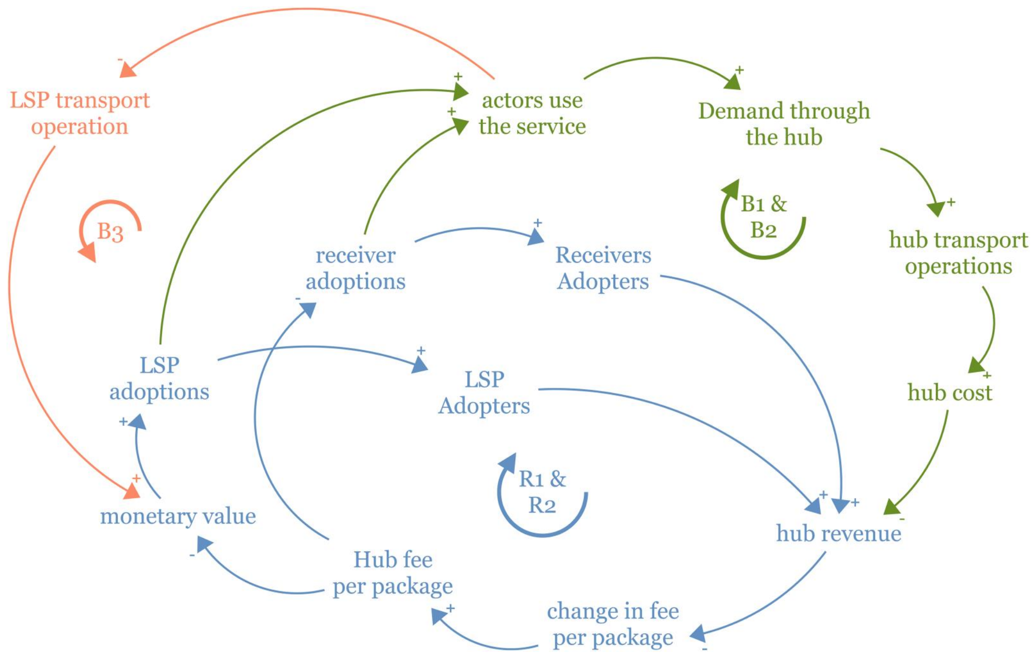

Figure 2. Causal Loop Diagram (CLD) showing the main dynamics studied in the model. The main variables are presented, connected by arrows showing the causal relationships. The positive (negative) arrows represent a positive (negative) causal relationship, meaning that an increase in the first variable causes an increase (a decrease) in the second variable. Reinforcing loops are marked as R, while balancing loops as B. Each loop has a different color and number to facilitate understanding.

zone in an area in the inner city, which occupies a central position within Stockholm.[1] This area presents a high concentration of office buildings, malls and shops, while only around 400 people live in the area (Trafikkontoret, 2024). Therefore, receivers are considered to be businesses with headquarters or shops in the area, and are divided into small, medium and large. In the area, there is a prevalence of small receivers. Its geography, characterized by multiple street levels and narrow streets, presents notable challenges for efficient delivery and renders deliveries by traditional means less profitable for LSPs. Moreover, several ongoing consolidation efforts offer valuable insights into the behavior of the diverse actors involved in Stockholm, such as the initiatives known as Älskade Stad (2023) (Beloved City), Upphandling Södertörn (Procurement in Södertörn) (Malmgren, 2022), Arenastaden and HITS2024.[2] Due to the environmental zone, the challenging geographical characteristics, and the similarity to other consolidation efforts in Stockholm, the inner city area selected by the City of Stockholm is chosen as a simulation area. Therefore, in this work, the transport operations that occur inside the area are considered. This means that all transport operations that have either an origin or a destination in the area are considered. However, only the kilometers that are traveled inside the area are considered, setting a clear system boundary for the simulation.

Within the chosen simulation area, data collection were performed through interviews and workshops. When the data regarding the flows within the chosen simulation area were not available, the data provided by the initiative of Arenastaden were used. The area of Arenastaden is similar due to the high concentration of office buildings and shops. Moreover, a consolidation center managed has been established in the area of Arenastaden by a third-party logistics service provider, acting as hub operator. This hub operator offers final delivery and return services (both package returns and recycling) to receivers such as stores and offices within the local mall and the surrounding areas. The different data sources are stated in the input tables for each module.

4. System dynamics model

Figure 2 shows the Causal Loop Diagram (CLD) with the main dynamics and feedback loops. At the core of the model there is the hub revenue which is affected by the loops “R1 & R2 - benefits of scale”. An increase in hub revenue prompts a decrease in change in fee per package, which in turn decreases the Hub Fee per Package. A decrease in Hub Fee per Package means that more LSPs and receivers are willing to adopt, which increases the hub revenue. The loops “R1 & R2 - benefits of scale” are reinforcing, and would lead to an exponential growth in hub revenue. However, the increase in LSP and receiver adoptions also leads to an increase in the number of actors using the service, and this to an increase in demand through the hub. This increase in demand through the hub increases in turn the hub transport operations and hub cost, which leads to an increase in change in fee per package, loops “B1 & B2 - costs of hub”. The loops “B1 & B2 - costs of hub” are balancing, bringing an increase in Hub Fee per Package, and balancing the exponential behavior of “R1 & R2 - benefits of scale”. A third loop influences the behavior of the LSPs, namely the loop “B3 - utilization of LSP resources”. An increase in actors using the service brings a decrease in the LSP transport operation

[1]https://trafik.stockholm/trafiksakerhet-trafikregler/miljozoner/miljozon-klass-3/. The area is delimited by the streets Kungsgatan, Birger Jarlsgatan, Hamngatan and Sveavägen. These streets are not included in the considered area.
[2]https://closer.lindholmen.se/en/project/hits-2024

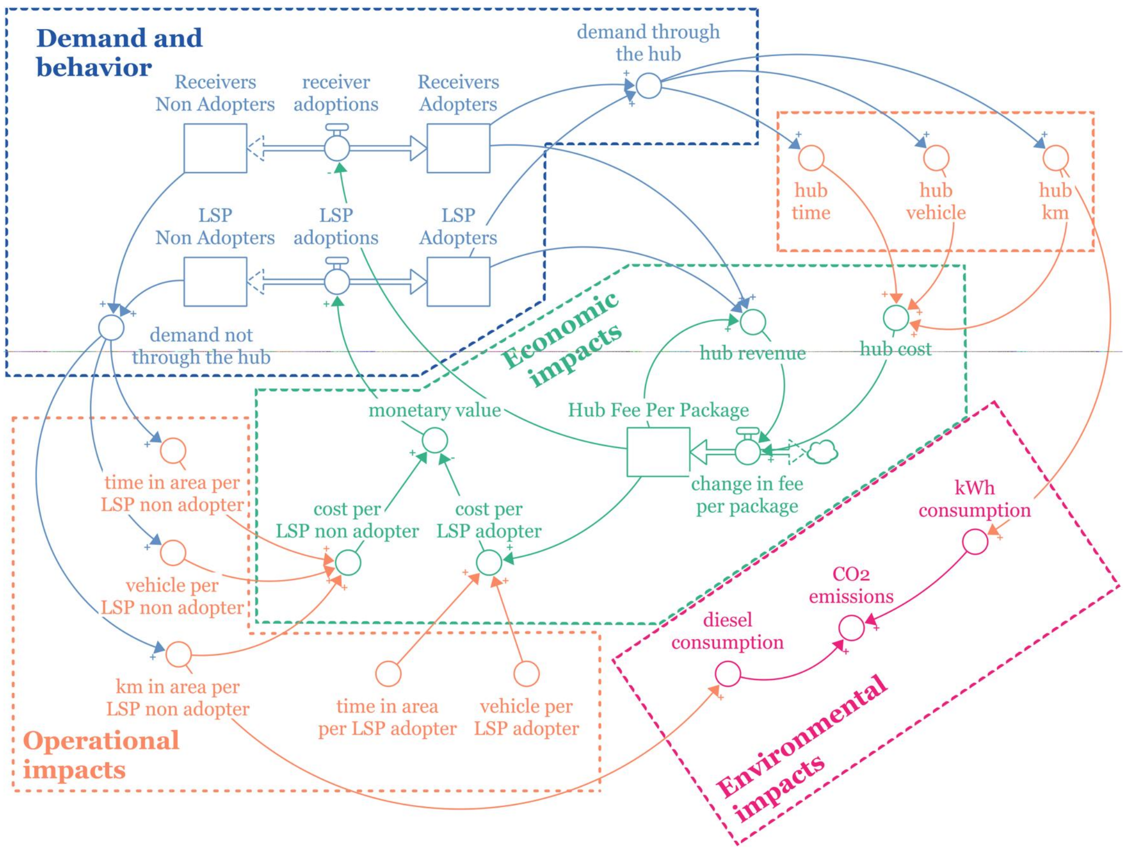

Figure 3. Simplified model view, with major stocks and flows and variables divided by module. The four modules are enclosed by dashed lines and are presented in different colors. Stocks are represented as rectangles, while flows are represented as arrows with control valve symbols. Other variables are represented as circles. The arrows connect variables, stocks and flows showing the causal relationships (see Figure 2 for explanation of the arrows).

cost. This means that receiver adoptions indirectly influence variables of LSP non-adopters. This occurs because receiver adopters redirect their packages to the hub, avoiding direct LSP deliveries. The monetary value, i.e., the representation of the willingness to join the service from the LSP perspective, is calculated as a comparison between the costs of the LSPs adopters and non-adopters. Therefore, the monetary value decreases when the LSP transport operation costs decrease. Subsequently, the loop "B3" is a balancing loop that balances the willingness to adopt the service from the LSP perspective.

In this paper, the simulation starts with no implemented city hubs, and therefore initially no demand through the hub and zero LSPs and receivers adoption. When hubs are introduced, the Hub Fee per Package is assumed to be very low or zero. This leads to adoption from both LSPs and receivers and a subsequent rise in demand through the hub. As demand through the hub rises, it drives up the hub cost, leading to an increase in change in fee per package. However, this Hub Fee per Package increase diminishes the perceived value for LSPs and receivers, decreasing their interest in the hub service. This decrease in interest creates a cause-effect relationship: the fee increase leads to decreased demand (balancing loops "B1 & B2 - costs of hub"). However, another dynamic emerges as receiver and LSP adoption boost the hub revenue, reducing the change in fee per package. This loop encourages more adoptions, balancing the initial impact of the fee on demand (reinforcing loop "R1 & R2 - benefits of scale").

An overview of the mathematical stock-flow model is shown in Figure 3. The model comprises four modules, depicted in different colors in Figure 3, each serving a specific function as outlined below. The entire model and its documentation is available upon request to the corresponding author.

- **Demand and behavior**. This module includes the assessment of the demand of goods to the area, and the behavioral patterns of actors, i.e., LSPs and receivers. The primary focus of this module is evaluating the utilization of the hub, from the demand and behavioral patterns.
- **Operational impacts**. Based on the demand of goods to the area and the hub utilization, the transport operations are calculated. It quantifies the number of vehicles, kilometers traveled, and delivery time, used as main outputs.
- **Economic impacts**. This module conducts a computation of expenses sustained by LSPs and receivers, factoring in transport operation and hub utilization. Moreover, the hub fee is also calculated, as a result of the revenue strategy of the hub operator.
- **Environmental impacts**. In this module, the transport emissions are quantified based on the transport operations and the behavioral patterns.

4.1. Demand and behavior

To model the demand for the hub service and the behaviors of the actors, the adoption of the hub service by the LSPs

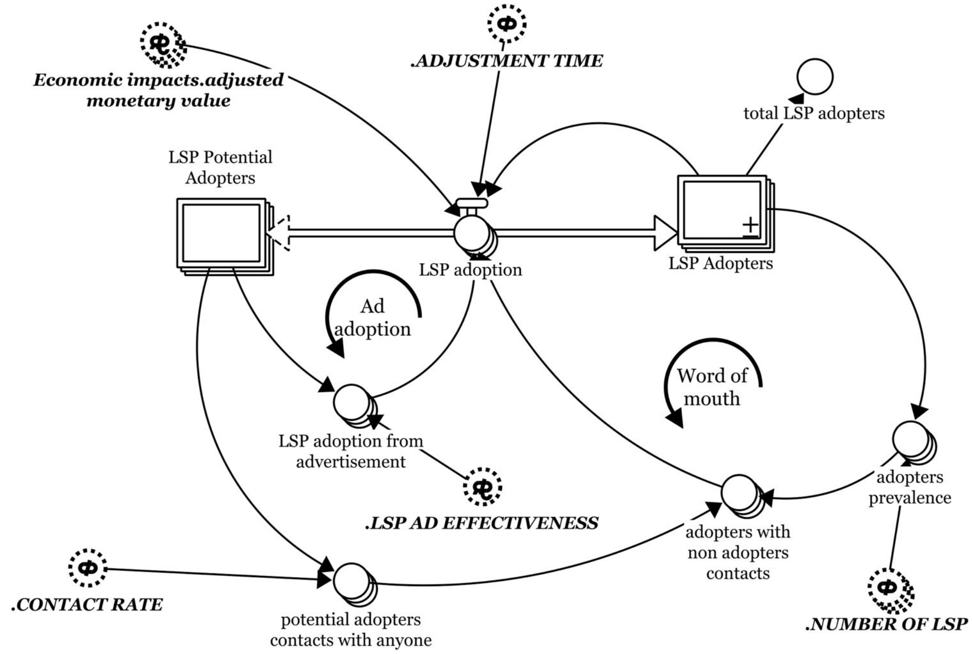

Figure 4. LSP adoption structure. Adapted from Sterman (2000) and Cagliano et al. (2017). Figure created by the author.

and receivers is simulated. The adoption dynamics are divided into three parts: the LSP adoption, the receivers adoption, and the calculation of the demand through the hub. The primary dynamic structure of the LSP adoption draws from the Bass model (referenced in Sterman (2000) and Cagliano et al. (2017)), outlined in Figure 4. Two stocks, LSP potential adopter and LSP Adopters, are connected *via* the flow of LSP adoption. The adoption is calculated by considering the adjusted monetary value, representing the economic incentive for the LSPs to join the hub scheme, as shown in Equation (1). Detailed explanation of the adjusted monetary value and its computation is provided in Section 4.3. When there is a positive monetary value, LSPs adopt the service *via* two streams. First, through advertisement adoption (as consequence of the *ad adoption* feedback loop) (Sterman, 2000), wherein the hub operator invests in initial advertisement impacting the adoption based on AD EFFECTIVENESS. The AD EFFECTIVENESS is part of the hub operator strategy and it is specified in each scenario. In the base scenario, it is considered to be zero. Second, through the *word of mouth* feedback loop, based on the interactions between adopters and non-adopters. This loop strengthens with the increase in the number of adopters (Sterman, 2000). Conversely, when there is no monetary incentive for LSP utilization of the service, the flow is negative (prompting adopters to revert to non-adopters within the ADJUSTMENT TIME).

$$\text{LSP adoption} = \text{IF adjusted monetary value} = 0$$
$$\text{THEN } \frac{\text{LSP Adopters}}{\text{ADJUSTMENT TIME}} \text{ ELSE adjusted monetary value}$$
$$\times \text{adopters with non adopters contacts} + \frac{\text{adoption from advertisement}}{\text{ADJUSTMENT TIME}} \tag{1}$$

The receivers adoption dynamic mirrors the structure of the LSP adoption, and is also rooted in the Bass model (sourced from Sterman (2000) and Cagliano et al. (2017)). However, unlike LSPs, receivers do not rely on a monetary value function for adoption. Rather, their decision hinges on the willingness to pay, referred to in the model as the RECEIVERS PERCEIVED VALUE. The RECEIVERS PERCEIVED VALUE is an input parameter that varies among receivers of different sizes, and it is elaborated on in the scenarios and the discussion section. The relationship between the receivers fee, the RECEIVERS PERCEIVED VALUE and the adoption rate is depicted in Table 1. The table shows that as the receivers fee increases, the adoption rate decreases, becoming negative when the receivers fee is higher than the perceived value. Similar to the LSP adoption, the *ad adoption* and *word of mouth* are the main feedback loops here. Based on the dynamics described in this paragraph, the receiver adoptions are computed following the formula presented in Equation (2).

Table 1. Relationship between the receivers fee, the RECEIVERS PERCEIVED VALUE and the adoption rate.

$\frac{\text{receivers fee}}{\text{RECEIVERS PERCEIVED VALUE}}$ (x)	0	0.25	0.5	0.75	1	1.25	1.5	1.75	2
Adoption rate (y)	0.2	0.15	0.1	0.05	0	−0.05	−0.1	−0.15	−0.2

$$\text{receivers adoption} = \text{IF adoption rate} > 0$$
$$\text{THEN adoption rate} \times \text{adopters with non adopters contacts}$$
$$+ \frac{\text{adoption from advertisement}}{\text{ADJUSTMENT TIME}}$$
$$\text{ELSE } \frac{\text{adoption rate} \times \text{Receivers Adopters}}{\text{ADJUSTMENT TIME}} \tag{2}$$

The calculation of the demand through the hub is divided in two parts. The total demand of all LSP adopters is calculated by multiplying the demand per LSP with the number of LSP Adopters. Since these LSPs adopt the hub service, this

Table 2. Combined input variables.

	Name	Base value	Unit	Source
Demand and behavior module	NUMBER OF LSP	[Small] = 69; [Medium] = 8; [Large] = 1	LSP	Case study
	SHARE OF DEMAND TO DIFFERENT LSP SIZES	[Small] = 0,08; [Medium] = 0,53; [Large] = 0,39	dmnl	Case study
	NUMBER OF RECEIVERS	[Small] = 172; [Medium] = 46; [Large] = 9	receiver	Case study
	DEMAND PER RECEIVER	[Small] = 30; [Medium] = 230; [Large] = 940	package/receiver /month	Case study
	RECEIVERS PERCEIVED VALUE	0	kr/month/receiver	Assumption
	CONTACT RATE	1	1/month	(Cagliano et al., 2017)
	ADJUSTMENT TIME	6	month	Assumption
	AD EFFECTIVENESS	0	dmnl	Assumption
Operational impacts module	PACKAGES PER STOP	[Small] = 1; [Medium] = 4; [Large] = 10	package/stop	(Iwan et al., 2021; Schonewille, 2015)
	DELIVERY TIME PER STOP	0,1	hour/stop	(Schonewille, 2015)
	DELIVERY TIME PER PACKAGE	0,07	hour/package	(Schonewille, 2015)
	KM PER STOP	0,45	km/stop	(Iwan et al., 2021)
	SPEED IN AREA	15	km/hour	(Katsela et al., 2022; Schonewille, 2015)
	TOURS PER MONTH	[Small] = 5; [Medium] = 10; [Large] = 20	1/month	Case study
	HUB VEHICLE CAPACITY	300	package/vehicle	Assumption
	LSP VEHICLE CAPACITY	500	package/vehicle	Assumption
	MAX OPERATING TIME OF VEHICLE	10	hour/day	Assumption
	TIME FOR UNLOADING TO THE HUB	0,01	hour/stop	Case study
Economic impacts module	COST PER DIESEL VEHICLE	4600	kr/vehicle/month	(Shojaei et al., 2022)
	COST PER ELECTRIC VEHICLE	3515	kr/vehicle/month	(Basma et al., 2022; Noll et al., 2022)
	COST PER kWh	2	kr/kWh	(Konsumenternas energimarknadsbyrå, 2023; SCB, 2023)
	COST PER LITER OF DIESEL	25	kr/liter	(Drivkraft Sverige, 2022)
	COST PER HOUR	270	kr/hour	(Friedrich and Elbert, 2022; Heeswijk et al., 2019; Katsela and Pålsson, 2021)
	HUB FIXED COST	54800	kr/month	(Katsela and Pålsson, 2021)
	ADJUSTMENT TIME FOR FEES	6	month	Assumption
	INITIAL FEE	0	kr/package	Assumption
	MAX INCREASE IN FEE	30	kr/package	Assumption
	PROFIT GOAL IN PERCENTAGE	0,01	dmnl	Assumption
Environmental impacts module	CARBON INTENSITY OF DIESEL	2,64	kgCO2/liter	(Basma et al., 2022)
	CARBON INTENSITY OF ELECTRICITY	0	gCO2/kWh	Assumption. Since only the emissions in the area are considered, the emissions per kWh are 0.
	kWh CONSUMPTION PER KM	0,4	kWh/km	(Iwan et al., 2021; Kin et al., 2021)
	LITER OF DIESEL PER KM	0,095	liter/km	(Basma et al., 2022; Noll et al., 2022)

demand is entirely going through the hub. However, part of the demand of LSP non-adopters is also going through the hub, if some of the receivers adopt the service. This demand is represented by the variable demand to hub of LSP non-adopter (Equation (3)). This value is then multiplied by the number of LSP Potential Adopters to calculate the total demand to hub of all LSP non-adopters. The demand through the hub is the sum of the total demand of all LSP adopters and the total demand to hub of all LSP non-adopters.

$$\text{demand to hub of LSP non adopter} = \frac{\text{Receivers Adopters} \times \text{DEMAND PER RECEIVER}}{\text{NUMBER OF RECEIVERS} \times \text{DEMAND PER RECEIVER}} \times \text{demand per LSP} \quad (3)$$

The demand and behavior module explained in this section uses the input values specified in Table 2. For the LSP and the receivers, the model includes three dimensions: *small*, *medium*, and *large*, based on how many packages are handled monthly. The number of packages per month for each category was already present in the data from Arenastaden, defined by the main transport operator. This division is made to account for differences in behavior stemming from the different sizes of actors. The outputs from this module encompass the demand through the hub, number of stops per LSP non-adopters, hub number of stops, and demand per LSP. These variables play a crucial role in other modules for computing transport operations and costs, described in the next sections.

4.2. Operational impacts

The operational impacts module serves to understand the costs associated with transportation at each time step. Unlike the other modules, structured around stocks and flows, this module operates statically, focusing on calculating the supply side of transportation corresponding to the demand side (given by the demand and behavior module). The output of this module are variables such as the number of stops, kilometers traveled, time for deliveries and number of vehicles that are needed to satisfy the demand. These outputs serve as essential inputs in the cost module, facilitating the computation of expenses incurred by various actors. The specifics of these calculations are elaborated in subsequent subsections. Table 2 lists the inputs for this module.

4.2.1. Number of stops

The number of stops for each delivery round is calculated in this module, both for the LSPs and for the hub service provider. The number of stops, a defining characteristic for each LSP, changes over time. PACKAGES PER STOP is an input parameter that refers to the number of packages unloaded by LSPs. The number of stops per LSP non-adopters is calculated considering the PACKAGES PER STOP and the demand per LSP non-adopter to be delivered to receivers (Equation (4)). The demand per LSP non-adopter to be delivered to receivers considers that the LSP Potential Adopters deliver part of their demand (i.e., demand to hub of LSP non-adopter) to the hub. Additionally, understanding the transport operation required from the hub involves computing the number of stops originating from the hub, as shown in Equation (5). This equation considers the MAXIMUM NUMBER OF STOPS PER MONTH PER RECEIVER, which is set to 20, as it is assumed that the hub does not visit the same receiver more than once every delivery tour.

$$\text{number of stops per LSP non adopters} = \frac{\text{demand per LSP non adopter to be delivered to receivers}}{\text{PACKAGES PER STOP}} \tag{4}$$

$$\text{hub number of stops} = \text{MIN}\left(\frac{\text{demand through the hub}}{\text{hub packages per stop}};\ \text{NUMBER OF RECEIVERS} \times \text{MAXIMUM NUMBER OF STOPS PER MONTH PER RECEIVER}\right) \tag{5}$$

4.2.2. Kilometers traveled

The computation of kilometers traveled involves a two-part process. Initially, goods travel from the LSP's distribution center (located outside the city boundaries) to the designated area for the case study. This leg of the journey is not considered in the model as it lies outside the system boundaries. Subsequently, if the LSP adopts the service, it transports the goods to the hub and returns to the distribution center at the same average speed. Therefore, km per LSP adopter is considered to be zero in the area. However, if the LSP doesn't adopt the service, it commences the delivery route within the area at a slower average speed. Goods delivered to the hub are thereafter transported within the area by the hub service provider at the same average speed after undergoing cross-consolidation in the hub. For the kilometers traveled within the area, a predefined number of kilometers per stop is assumed (as indicated in Table 2), considering the number of stops calculated in the demand and behavior module (Equations (6) and (7)).

$$\text{km in area per LSP non adopter} = \text{number of stops per LSP non adopters} \times \text{KM PER STOP} \tag{6}$$

$$\text{km per hub} = \text{hub number of stops} \times \text{KM PER STOP} \tag{7}$$

4.2.3. Time for deliveries

The computation of the time taken to deliver the goods involves considering three components: the time to get to the area, the time for traveling between stops in the area, and the time for stopping and delivering goods. The time to get to the area is considered for the LSPs, even if it lies outside of the boundaries of the system, as it needs to be considered when calculating the number of vehicles needed, see Section 4.2.4. The time taken to get to the area and the time for traveling between stops are calculated considering the average speed within various areas, applying Equation (8) to the outcomes from the kilometers calculation. In this equation, d represents the number of kilometers, v denotes the speed, and t signifies the time.

$$t = \frac{d}{v} \tag{8}$$

The time for stopping and delivering goods is determined by combining the time taken to locate a stop (parking time) with the time needed to actually deliver packages to the receivers. This time depends on the number of stops and on the number of packages unloaded at each stop. LSP Adopters only stop at the hub, while LSP Potential Adopters stop at each receiver, and at the hub if there are some receivers that adopted the service. The total time is shown below.

$$\begin{aligned}\text{time in area per LSP non adopter} &= \text{time for stops per LSP non adopter} \\ &\quad + \text{time for delivering packages per LSP non adopter} + \text{time for unloading to the hub per LSP non adopter} \\ &= (\text{DELIVERY TIME PER STOP} \times \text{number of stops per LSP non adopters}) \\ &\quad + (\text{DELIVERY TIME PER PACKAGE} \times \text{demand per LSP non adopter to be delivered to receivers}) \\ &\quad + (\text{TIME FOR UNLOADING TO THE HUB} \times \text{demand to hub of LSP non adopter})\end{aligned} \tag{9}$$

$$\text{time in area per LSP adopter} = \text{TIME FOR UNLOADING TO THE HUB} \times \text{demand per LSP} \tag{10}$$

4.2.4. Number of vehicles

The determination of the required number of vehicles involves considering the number of packages to be transported per tour and the time per tour. The number of vehicles is constraint either by the relation between its capacity and the number of packages per tour, or by the relation between its maximum operating time and the time per tour. From the MAX OPERATING TIME OF VEHICLE, the time to and from area is subtracted. The time per tour is calculated by diving the time in area by the number of tours per month. LSP Potential Adopters require a number of vehicles, as specified in Equation (11). vehicle per LSP adopter and the hub vehicles are calculated using similar formulations, considering different times and vehicle capacities.

$$\text{vehicle per LSP non adopter} = \text{MAX}\left(\frac{\text{demand per LSP}}{\text{TOURS PER MONTH} \times \text{LSP VEHICLE CAPACITY}}, \frac{\text{time per tour per LSP non adopter}}{\text{MAX OPERATING TIME OF VEHICLE} - \text{time to and from area}}\right) \tag{11}$$

4.3. Economic impacts

The economic impacts module is split into two parts: one focusing on computing the expenses associated with the LSPs and another dedicated to evaluating the costs related to the hub. Additionally, the Hub Fee per Package is computed in this module. The input variables for this module are outlined in Table 2. The main outputs are the monetary value and the fee per package.

Much of the input for this section is derived from the transport operation module. The cost breakdown comprises three components: cost per time, cost per kilometer, and cost per vehicle. The cost per time represents the expenditure incurred by the LSPs for their employees. The input variable COST PER HOUR is employed as the hourly salary for the employees. Meanwhile, the cost per kilometer mainly encompasses fuel expenses. Distinct fuel costs are assumed for LSPs using diesel vehicles and the hub operator using electric vehicles. Additionally, the cost per vehicle accounts for the vehicle purchase cost, divided by the vehicle's expected operational duration. This cost per vehicle varies between diesel and electric vehicles.

The cost per LSP non-adopters and the cost per LSP adopters are computed as the sum of these different costs, as detailed in Equations (12) and (13). Notably, the cost per LSP adopters also includes the hub fee. The determination of the monetary value is based on the maximum between 0 and the ratio of the difference between the two costs divided by the initial value of the cost per LSP non-adopters, expressed in Equation (14). This computation results in a monetary value ranging between 0 and 1. Further adjustments are made to this monetary value using a table function outlined in Table 3. Here, the "x" represents the monetary value, and "y" denotes the adjusted monetary value. This adjustment accounts for a minimum cost saving threshold necessary to justify the LSPs' behavioral change. In our context, this threshold is set at 10%, thereby shifting the adjusted monetary value by 10%. Subsequently, this adjusted monetary value is applied in the demand and behavior module to determine the LSPs' behavior.

Table 3. Monetary value (x) and corresponding adjusted monetary value (y).

Monetary value (x)	0	0,1	0,2	0,3	0,4	0,5	0,6	0,7	0,8	0,9	1
Adjusted monetary value (y)	0	0	0,1	0,2	0,3	0,4	0,5	0,6	0,7	0,8	0,9

$$\text{cost per LSP non adopters} = \text{hour cost per LSP non adopters} + \text{km cost per LSP non adopter} + \text{LSP vehicle cost} \tag{12}$$

$$\text{cost per LSP adopters} = \text{hour cost per LSP adopters} + \text{LSP vehicle cost} + \text{LSP fee} \tag{13}$$

$$\text{monetary value} = \text{MAX}\left(0, \frac{\text{INIT(cost per LSP non adopters)} - \text{cost per LSP adopters}}{\text{INIT(cost per LSP non adopters)}}\right) \tag{14}$$

Similar to the process for determining the LSP costs, the hub cost consists of the sum of hub time cost, hub km cost, and hub vehicle cost, based on values calculated in the transport operation module. In addition, the HUB FIXED COST is included in the hub cost. The fixed costs include operational expenses (e.g., electricity, water, heating) and a full-time employee wage (refer to Table 2). The total cost of operation is calculated as the sum of the operational costs of the LSPs and the hub cost, as in Equation (15).

$$\text{total cost of operation} = \text{LSP Potential Adopters} \times \text{cost per LSP non adopters} + \text{LSP Adopters} \times (\text{cost per LSP adopters} - \text{LSP fee}) + \text{hub cost} \tag{15}$$

4.3.1. Hub fee dynamics

In this module, the Hub Fee per Package is determined through a stock-flow structure (Figure 5). The flow, change in fee per package, is calculated using Equation (16), wherein the binary time for fees is a variable maintaining a value of one during each period of ADJUSTMENT TIME FOR FEES. This structure is modeled akin to the goal and gap stock-and-flow formulation (referenced in Sterman, 2000). The hub revenue is determined by summing the receiver and LSPs payments of the fee. The revenue gap represents the difference between the revenue goal and the revenue for fee calculation presented as a percentage (Equation

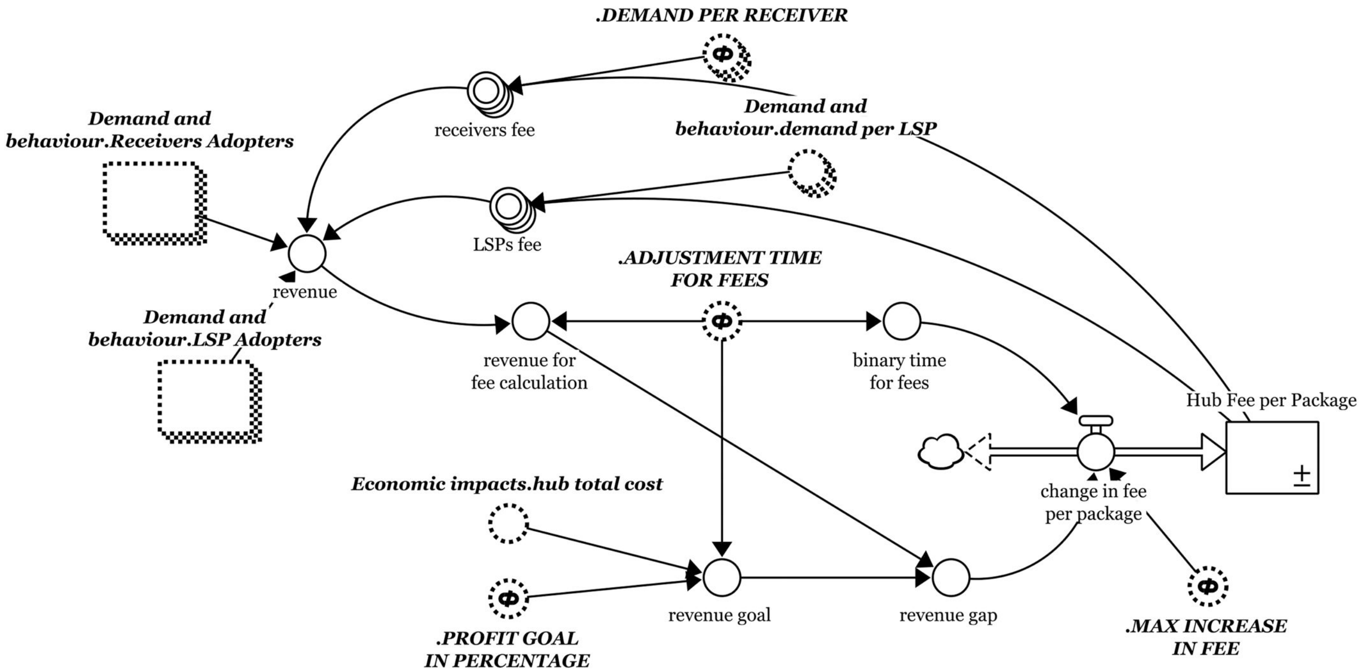

Figure 5. Representation of the hub fee dynamics.

(17)). It can also be negative, inducing a decrease in the Hub Fee per Package to adjust the revenue toward the goal. Both the revenue for fee calculation and the revenue goal are computed utilizing the smooth (SMTH) function, an embedded function performing first-order exponential smoothing with an exponential averaging time set to the ADJUSTMENT TIME FOR FEES. The revenue for fee calculation is derived from the revenue, while the revenue goal from the hub's cost multiplied by 1 + PROFIT GOAL IN PERCENTAGE. Once the Hub Fee per Package is determined, the LSP fee and the receivers fee are calculated by multiplying the Hub Fee per Package with the number of packages delivered or received, respectively.

$$\begin{aligned} \text{change in fee per package} = {} & \text{IF binary time for fees} = 1 \\ & \text{THEN } \frac{\text{MAX INCREASE IN FEE} \times \text{revenue gap}}{\text{binary time for fees}} \\ & \text{ELSE } 0 \end{aligned} \tag{16}$$

$$\begin{aligned} \text{revenue gap} = {} & \text{IF revenue for fee calculation} = 1 \\ & \text{THEN } 1 \\ & \text{ELSE } \frac{\text{revenue goal} - \text{revenue for fee calculation}}{\text{revenue goal}} \end{aligned} \tag{17}$$

4.4. Environmental impacts

Similar to the operational impacts module, the environmental impacts module doesn't involve dynamics but computes emissions statically based on kilometers traveled by diesel and electric vehicles. This module does not have any stocks, flows, or outputs. The kWh consumption is determined by multiplying the kWh CONSUMPTION PER KM with the kilometers traveled in the area by the hub. Notably, CO2 emissions from electricity are negligible, as the system boundary is the border of the simulation area, and electric vehicles produce zero tailpipe emissions. The diesel consumption is computed using Equation (18). Diesel consumption is derived by multiplying the kilometers traveled by the exogenous variable LITER OF DIESEL PER KM.

$$\begin{aligned} \text{diesel consumption} = {} & \text{diesel consumption per LSP non adopter} \\ & \times (\text{NUMBER OF LSP} \\ & - \text{LSP Adopters}) \end{aligned} \tag{18}$$

4.5. Model testing

To ensure the reliability of the model, different types of tests are performed, following the method proposed by Sterman (2000). The structure is assessed using interviews and the previous literature, together with the case studies in Stockholm. In each equation dimensional consistency is ensured, without the use of additional parameters. The parameters are assessed to make sure that they have real world counterparts, even if qualitative. Extreme conditions are also tested, to check that the model performed in a reasonable way to large shocks in input data. Moreover, the model results and behavior have been compared to previous literature, as detailed below.

To test that the model results and behavior are comparable to previous efforts in the literature, two simulations have been carried out. First, a simulation with no hub solution. This scenario represents the system as it is at present. Second, a simulation where the hub is utilized fully, i.e., all demand that enters the area is handled by the hub operator. This second simulation is a result of a forced behavior in the model, where the hub fee dynamics is not considered. The result of this simulation are reported in Table 4. The results presented in the table are in accordance with other simulation results in the literature, i.e., Nocera and

Table 4. Comparison between no hub scenario and full utilization scenario.

Variable	No hub	Full utilization	% reduction in Full utilization compared to No hub
Total cost of operation	1.15 MSEK	1.01 MSEK	13%
Total number of km traveled in the area	2740 km	545 km	80%
Total number of vehicles in the area	91	10	89%

Table 5. Sensitivity analysis for the no hub scenario on the variable *cost per LSP non-adopters*.

Input		Output		
Variable name	Base value	Change in cost −20%	Change in cost +20%	LSP size
LSP VEHICLE CAPACITY	500	0%;	0%;	Small;
		0%;	0%;	Medium;
		0%	0%	Large
KM PER STOP	0,45	−1%;	1%;	Small;
		−1%;	1%;	Medium;
		−1%	0%	Large
DELIVERY TIME PER STOP	0,1	−2%;	2%;	Small;
		−4%;	4%;	Medium;
		−3%	2%	Large
DELIVERY TIME PER PACKAGE	0,07	−2%;	2%;	Small;
		−11%;	11%;	Medium;
		−17%	15%	Large
TOURS PER MONTH	5;	0%;	0%;	Small;
	10;	9%;	0%;	Medium;
	20	2%	−2%	Large
PACKAGES PER STOP	1;	4%;	−3%;	Small;
	4;	7%;	−4%;	Medium;
	10	3%	−3%	Large

The first column shows the name of the variable that varies in the sensitivity. The second column shows the base value of such variable, while the third and fourth column show the +20% and −20% variation of the variable. Finally, the fifth and sixth column show the result in terms of cost per LSP non-adopters relative to the base value, in case of +20% and −20% variation of the variable, respectively.

Table 6. Different scenarios with their main dynamics.

Scenario name	LSP fee	Receiver fee	Cost calculation	Main dynamics of the hub revenue flows	Motivating questions
LSP only	x		N/A	The hub service is offered to LSPs only. The LSPs are willing to adopt the hub service and pay the fee as long as it is profitable for them.	Is it cost-effective for the LSPs to use the service?
Receiver only		x	N/A	The hub service is offered to receivers only, who adopt the service based on word of mouth and advertisement, and pay a fee that covers the hub costs.	How much should the receivers fee be for the hub to make profit?
Static cost	x	x	Static	The hub service is offered to both the LSPs and receivers. The LSPs are willing to pay the fee as long as it is profitable for them compared to a no hub scenario. The receivers adopt the service and pay the fee to cover the remaining costs for the hub.	How much should the receivers fee be for the hub to make profit, if the LSPs share part of the costs?
Dynamic cost	x	x	Dynamic	The hub service is offered to both the LSPs and receivers. The LSPs are willing to pay the fee as long as it is profitable for them considering the change in cost per LSP non-adopters due to the receivers adoption.	How much should the receivers fee be for the hub to make profit, if the LSPs share part of the costs?

Cavallaro (2017); Isa et al. (2020); Rabe et al. (2018); Paddeu (2021); Wasiak et al. (2017); Heeswijk et al. (2019); Nataraj et al. (2019).

Moreover, a simplified sensitivity analysis has been carried out considering the most uncertain input variables in the model. The results of the sensitivity are shown for the no hub scenario in Table 5. According to the table, the variables that affect the most the cost per LSP non-adopters are PACKAGES PER STOP and DELIVERY TIME PER PACKAGE. These two variables are used in further sensitivity analysis in the specific scenarios, explored in the next section.

5. Simulated scenarios and results

The model is applied to four scenarios with different pricing strategies of the hub operator. The scenarios and the detailed results are presented in this section. Table 6 provides an overview the different scenarios and summarizes the main dynamics of the hub revenue flows, which differ in each scenario.

In the *LSP only* scenario, the hub service is targeted to the LSPs only, and the hub delivers all the packages of each LSP that decides to adopt the service. These number of LSP adopters over time is shown in Figure 6d–f). As it can be argued that LSPs aim at reducing their urban logistics operations costs, the motivating question for this scenario is

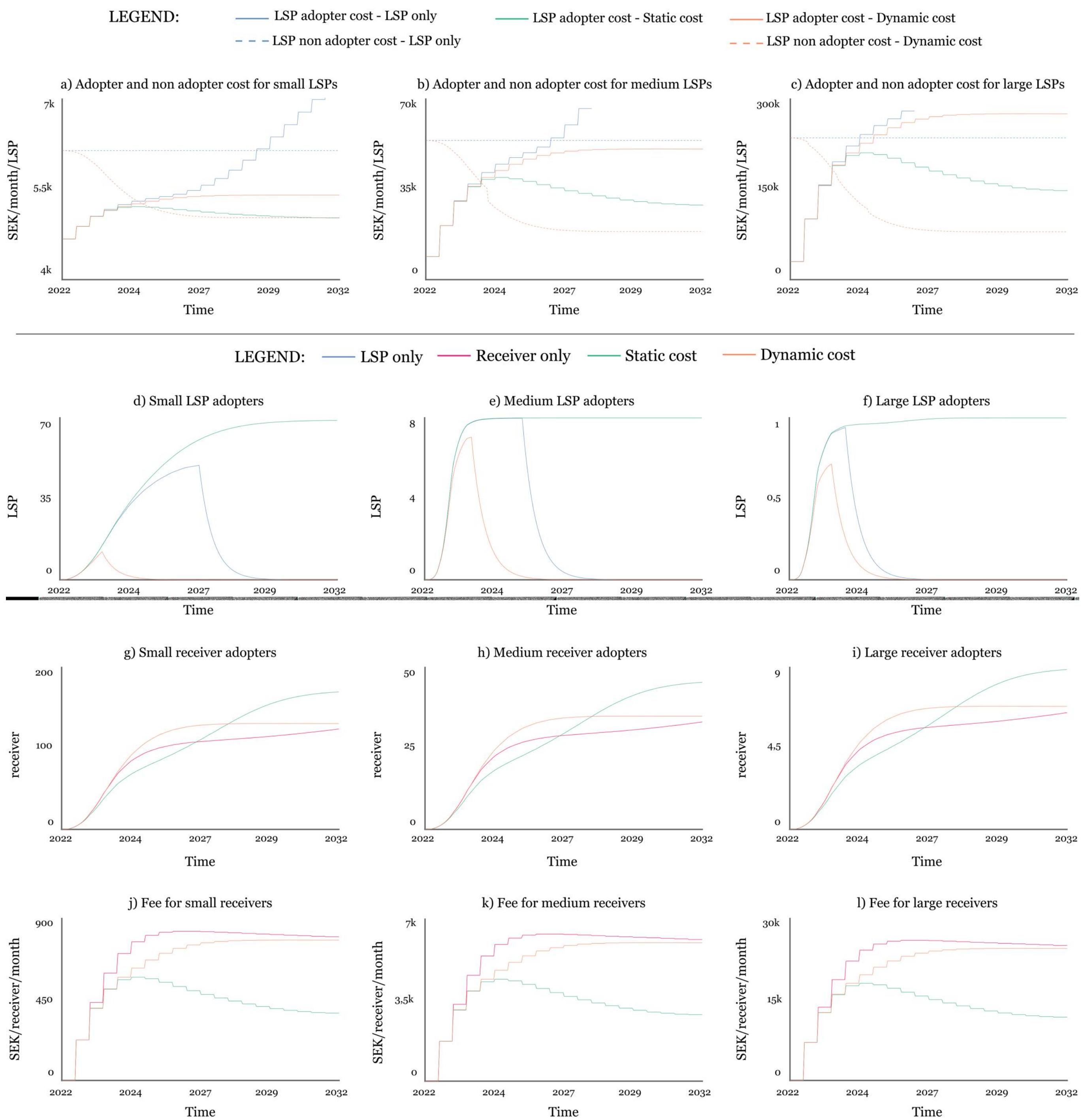

Figure 6. Results from the scenarios. (a, b and c) The difference between the adopter and non-adopter cost for small, medium and large LSPs respectively. (d, e and f) The adoption curves for small, medium and large LSPs respectively. (g, h and i) The adoption curves for small, medium and large receivers respectively. (j, k and l) The fees for small, medium and large receivers respectively.

whether it is cost-effective for the LSPs to use the service. The blue curves in Figure 6a–c show that, in the *LSP only* scenario, a few years after implementation the cost per LSP adopters (solid blue) exceeds the cost per LSP non-adopters (dashed blue). Thus, our model shows that the service is not economically viable on the long-term if it only targets LSPs. A more nuanced picture emerges when differentiating among different sized LSPs. Larger and medium LSPs reach the point where the cost per LSP adopters (solid blue) meets the cost per LSP non-adopters (dashed blue) earlier than small LSPs (Figure 6a–c). This is reflected in the adoptions, shown in Figures 6d–f.

In the *Receiver only* scenario, the hub service is targeted to the receivers only, and it is assumed that when a receiver joins the service all their goods are delivered by the LSP to the hub and then from the hub to the receiver. Since it is assumed that the shipping price that the receivers have to pay to the LPS does not change, the service of the hub implies an extra cost for the receiver. Therefore, the question in this scenario is how much the receivers fee needs to be, if the receivers were the only ones to cover the cost for the hub service. The red curves in Figure 6j–l show how the fee increases until they reach steady levels at approximately 800, 6,100 and 25,000 SEK/month for the small, medium and large receivers respectively. The receiver fee reaches its equilibrium level approximately at the same time for all receivers sizes.

In the *Static cost* scenario, the hub service is targeted to both receivers and LSPs. If both the receivers and the LSPs share the cost of the hub, the hypothesis is that it could be beneficial for both of them. Therefore, the question in this scenario is how much the receivers fee needs to be to make the hub service sustainable, if the LSPs share part of the costs. In this scenario, the monetary value for LSPs is calculated using a constant cost per LSP non-adopters, equal to its initial value. The green lines in Figures 6a–c show how the cost for the LSP adopters stabilizes after a few years, at a cost that is lower than the non-adopter cost for all LSP sizes. The green curves in Figure 6j–l show how the fee increases until they reach steady levels at approximately 375, 2,900 and 12,000 SEK/month for the small, medium and large receivers respectively. The receiver fee reaches its equilibrium level approximately at the same time for all receivers sizes.

In the *Dynamic cost* scenario, the monetary value is calculated considering that receivers adopting the service changes the cost per LSP non-adopters. When receivers adopt the service, also non-adopters LSPs deliver part of their parcels to the hub (i.e., the ones destined to the receivers who have adopted the service) and therefore have lower operational costs. This change is reflected in the monetary value equation, which is substituted with Equation (19) from Equation (14). The results of this scenario show some similarities to those of the *Receiver only* scenario, because the LSPs tend to leave the hub service as soon as they see that receivers are willing to pay for the costs.

$$\text{monetary value} = \text{MAX}\left(0, \frac{\text{cost per LSP non adopters} - \text{cost per LSP adopters}}{\text{cost per LSP non adopters}}\right) \tag{19}$$

Figure 7 shows the model outputs in the different scenarios. From these graphs, it is evident that the hub is successful in the *receiver only*, *static cost* and *dynamic cost* scenarios. Figure 7a–c) show the reduction of CO2 emissions, total kilometers traveled in the area and total vehicles in the area. The scenario where the reductions are achieved fastest is the *static cost* scenario. The reduction of total operation cost, Figure 7d, is less evident. Figure 7e shows the total system cost, which increases in all scenarios. The total system cost is calculated by adding to the total operational cost the revenue of the hub. The reason for the sudden changes in total operational costs is that the Hub Fee per Package is changed only once every ADJUSTMENT TIME FOR FEES, leading to discontinuous behavior. The *static cost* scenario reveals the highest increase, around 60%. Figure 7f shows the demand through the hub in the various scenarios.

5.1. Sensitivity analysis

A sensitivity analysis was performed to explore the influence of different parameters. The following parameters are modified in the sensitivity analysis: PACKAGES PER STOP, DELIVERY TIME PER PACKAGE, HUB FIXED COST, MAX INCREASE IN FEE, TIME FOR UNLOADING TO THE HUB and RECEIVERS PERCEIVED VALUE. Each variable underwent an Ad-Hoc distribution, a method of assigning specific values to variables, encompassing three specific points (-20%, base value, and +20%) and opting for the all-combination approach, which involves testing every

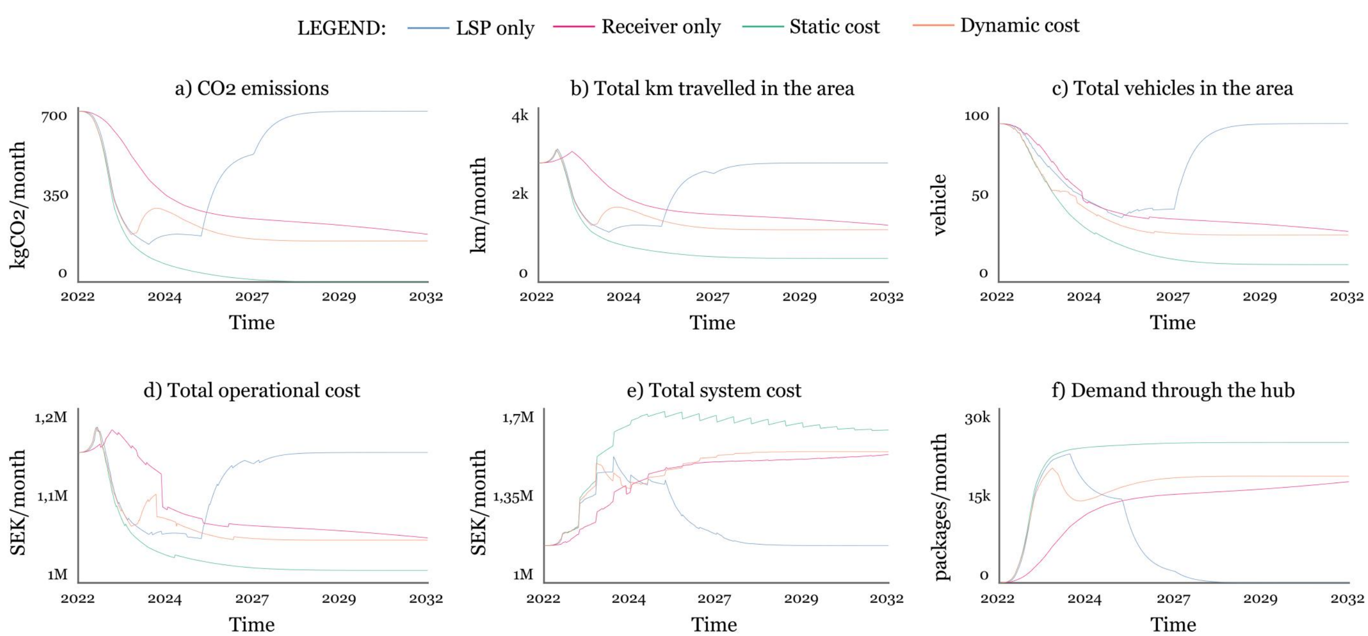

Figure 7. Comparison of scenario results in terms of CO2 emissions, total kilometers traveled in the area, total vehicles in the area, total operation cost, total system cost, hub revenue and cost.

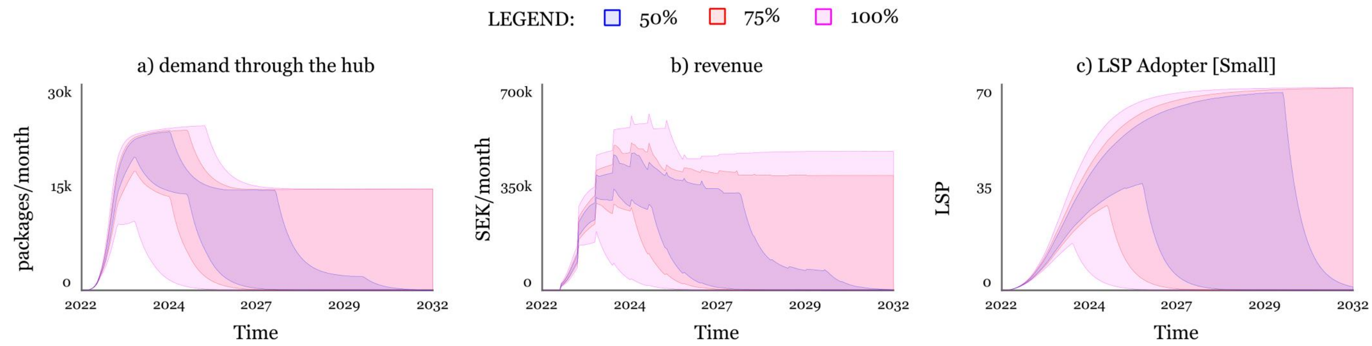

Figure 8. Multivariate analysis for the *LSP only* scenario.

Figure 9. Sensitivity analysis for the *static cost* scenario.

possible combination of these values. The sensitivity analysis was executed for two scenarios: *LSP only* and *static cost*. In the case of the *LSP only* scenario, the variable RECEIVERS PERCEIVED VALUE was omitted from consideration, given the absence of receivers. Consequently, there were 243 unique combinations (i.e., 243 runs) for the *LSP only* scenario. Figure 8 shows the confidence intervals of the results of the sensitivity analysis of the *LSP only* scenario. For the *static cost* scenario, all variables were incorporated, resulting in 729 combinations (i.e., 729 runs). Figure 9 shows the confidence intervals of the results of the sensitivity analysis of the *static cost* scenario.

Figure 8 shows that, in more than 50% of the simulation runs, the adoption of LSPs alone is not enough to sustain the cost of the hub. This behavior can be recognized in the demand through the hub and revenue collapse in Figures 8a and b. Furthermore, no combination of parameters exists that makes using the hub convenient for large LSPs, hence leveraging only small and medium LSPs to be partially profitable. For this reason, were only LSPs to adopt the service, the hub would never reach its full utilization (i.e., the demand through the hub is always below 100%, as shown in Figure 8a given the uncertainties specified in this sensitivity analysis.

On the contrary, when also receivers are involved, the hub may reach its full potential. Figure 9 shows that, in more than 25% of the simulation runs, the adoption of LSPs and receivers is enough to sustain the cost of the hubs, and the demand through the hub reaches 100% (Figure 9a). However, in 12.5% of the simulation runs, revenue collapses, together with both LSP and receiver adopters. In another 12.5% of the runs the revenue is likely to collapses, while in 50% of the runs the revenue doesn't collapse in this time frame, but shows a declining trend which would likely result for the hub to be unsustainable in the future (Figure 9b).

This sensitivity analysis shows that the model results are sensitive to a variation of the input parameters. However, in the majority of sensitivity analysis simulations, the overall dynamics of the actors involved remain the same as those of the base value. Therefore, there is a numerical sensitivity (i.e., a change of assumption changes the numerical values) but not a strong behavior model sensitivity (i.e., a change of assumption changes the behavior generated by the model) (Sterman, 2000). A more comprehensive sensitivity analysis would require testing more combinations of assumptions in all scenarios, but it would be an overwhelming amount of simulation runs. Therefore, the focus is on those parameters suspected to be both highly uncertain and likely to be influential, as specified by Sterman (2000).

5.2. Consideration on the environmental zone

In the case study area, as mentioned in 3.2, an environmental zone will be implemented at the end of 2024.[3] In the environmental zone, the technologies allowed for light-duty vehicles are: Battery Electric Vehicles (BEVs), Liquid Natural Gas (LNG) engines with Euro 6 emission standards, and fuel cells electrice vehicls (FCEVs). For heavy-duty vehicles, the allowed technologies are the same as above but also include plug-in hybrid (PHEVs) meeting Euro 6 standards. The implementation of the environmental zone will significantly impact the costs of the LSPs delivering in the area, since they will have to purchase new electric vehicles.

[3]https://trafik.stockholm/trafiksakerhet-trafikregler/miljozoner/miljozon-klass-3/

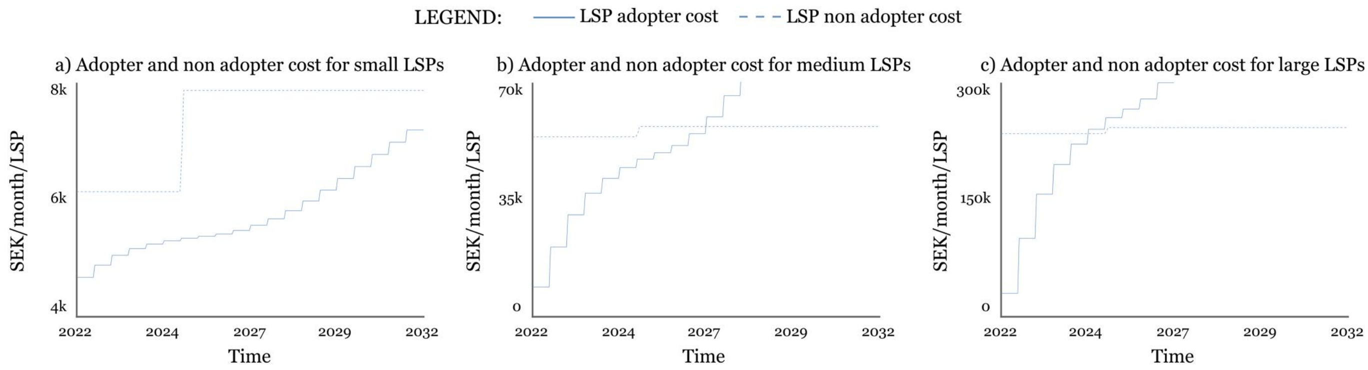

Figure 10. Scenario *LSP only* considering the environmental zone regulation.

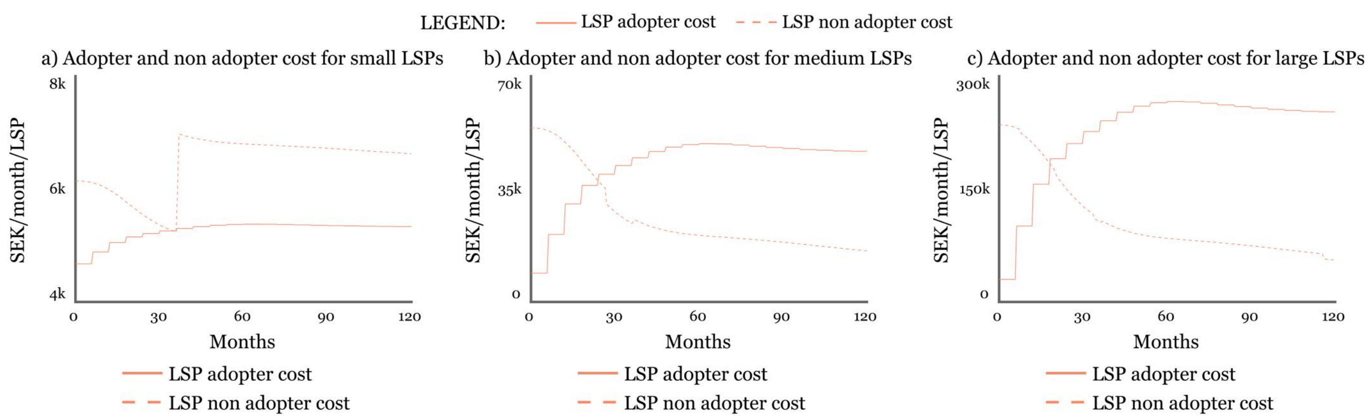

Figure 11. Scenario *dynamic cost* considering the environmental zone regulation.

Two scenarios, i.e., *LSP only* and *dynamic cost*, are simulated with implementing the environmental zone from the 31st of December, 2024. In the simulation model, the implementation of the environmental zone was implemented as an increase in the cost of ownership of LSP vehicles and by assuming that the new vehicles run on electricity. Figure 10 shows the results of the adopter and non-adopter costs of small, medium and large LSPs in scenario *LSP only*. The blue dashed line in Figure 10a shows the non-adopter cost of small LSPs. It is evident how, at the beginning of 2025, the cost for small adopters increased significantly. The increase is not as significant for the other LSP sizes (Figure 10b and c). In this scenario, it is convenient to join the hub service only for the small adopters. However, in the long run, the cost for small LSP adopters is expected to increase over the LSP non-adopter cost (as evident by the trend in Figure 10a).

Figure 11 shows the results of the adopter and non-adopter cost in scenario *dynamic cost*. Similarly to the previous case, the non-adopter costs increases dis-proportionally for the different LSP sizes, with a larger impact for small LSPs. However, Figure 11a shows that, with the increase in cost and the receivers' participation in the hub scheme, it is convenient for small LSPs to adopt the hub service.

6. Discussion

6.1. Conditions for economical sustainability

The results presented in Section 5 illustrate the impacts of different pricing strategies of the hub operator. In all scenarios where the hub is successful (i.e., all scenarios except *LSP only*), reaching a critical mass is crucial to reduce transport-related externalities and achieve economies of scale, as underlined in previous studies such as Simoni et al. (2018). The total cost of operation at a system-level reduces in most scenarios where the city hub implementation is successful, which is in line with Paddeu (2021) and Estrada and Roca-Riu (2017). However, the total system cost rises in all scenarios where the hub is successful. This result indicates that achieving sustainability through city hubs is not cost-effective. Moreover, this result explains also why the *LSP only* scenario is not successful: if the LSPs are the only actor bearing the costs of the hub, their fee would be higher than the reduction in their cost of operations. The existing literature (e.g., Akgün et al., 2020; Björklund & Johansson, 2018; Nataraj et al., 2019; Paddeu & Parkhurst, 2020) confirms these results by identifying the increase in cost as the main barrier to city hub adoption. The hub is successful in all other scenarios as the receivers are also participating in paying the fee, reducing the economic burden on LSPs.

It must be noted that the quantification of the receivers' benefits is not added to the model, even though the total system cost includes the fee paid by the receivers. One key benefit of receiving deliveries through the city hub is the lower number of deliveries (which in turn results in fewer interruptions for the personnel in reception) (Gammelgaard et al., 2016; Johansson and Björklund, 2017). Moreover, the hub operator could provide value-added services such as storing goods at the city hub location or unpacking larger consignments (Gammelgaard et al., 2016; Johansson and Björklund, 2017). Therefore, including these benefits might decrease the total system cost and lead to a higher willingness to participate from the receivers' perspective.

For the LSPs, the time-based costs constitute the highest portion of delivery costs for most LSPs (as in Janjevic and Ndiaye (2017) and Estrada and Roca-Riu (2017)). Therefore, the hub operator provides valuable service to the LSPs by reducing their time-based costs. However, the time savings gained by consolidation are insufficient to compensate for the increase in the fee per LSP. Moreover, the hub service is more attractive for small-sized LSPs. These results align with the previous literature (Browne et al., 2005; Janjevic and Ndiaye, 2017), which specifies that city hubs are more profitable for actors with lower demand in the area. According to Estrada and Roca-Riu (2017), if the unit cost saving of the LSPs is higher than the unit cost of the hub operator, the potential cost savings of the LSPs should be enough to pay a fee to the hub operator, a win-to-win collaboration should be possible. The authors propose boundaries and limitations to achieving these conditions in their paper, based on the density of receivers and the distribution of the parcel volumes delivered by the city hub (Estrada and Roca-Riu, 2017). According to Estrada and Roca-Riu (2017), the high density of receivers is a positive factor for the city hub implementation. In our study, the density of receivers is very high (1,000 receivers per square kilometer), which would indicate a successful city hub implementation even with just LSPs involved. These indications go against the results of our study. However, the density of receivers in the NoHa area is higher than the boundaries of the Estrada and Roca-Riu (2017) study (400 receivers per square kilometer).

In the *receivers only* scenario, the pricing strategy of the hub operator is to target the receivers. Similarly, Paddeu (2017) explore the receivers' perspective on adopting the service. The authors find that the city hub scheme works well in the Bristol-Bath consolidation case study due to the receivers' participation (i.e., receivers guarantee enough demand for the hub to be efficient) and public funding. However, the service is expected to have financial issues if such public funding should stop (Paddeu, 2017). Nordtømme et al. (2015) study the process of implementing a city hub in Oslo and its failure after the time frame of the initial project, mainly due to financial barriers. These possible financial issues pointed out by both Paddeu (2017) and Nordtømme et al. (2015) align with our research results, as the receivers' fee proves to be very high in scenarios where the receivers are the only source of revenue for the hub operator. The question is whether the receivers would be willing to pay this high fee to be part of the hub. However, Nordtømme et al. (2015) finds that the receivers' involvement is low, as they are reluctant to change their present delivery arrangements. One possibility would be for the LSPs to reduce the delivery price for receivers who are part of the hub scheme. These additional dynamics have not been studied in our model but could be explored further in future work.

The answer to the first research question, i.e., under what conditions city hubs are sustainable, is complex. In the *static cost* scenario, transport-related externalities are reduced most quickly through the collaboration of both LSPs and receivers. However, it is not guaranteed that this is an economically sustainable scenario. As pointed out by Akgün et al. (2020) and Björklund and Johansson (2018), managing actors with different goals (i.e., the LSPs and the receivers), costs and benefits through a hub service is challenging. The assumption that LSPs use a static cost calculation, as in the *static cost* scenario, is quite strong, and it might be more likely that LSPs use a dynamic cost calculation, as in the *dynamic cost* scenario. In that case, including receivers and LSPs is not economically sustainable. In the *dynamic cost* scenario, as soon as the receivers adopt the service, the LSPs realize that another actor is willing to pay for the service and drop out to avoid the extra hub fee. In particular, it is clear that with only LSPs' or receivers' participation, the hub operator will likely not have enough profit to sustain operations. Therefore, it is critical to either achieve collaboration between the different actors or to focus on the role of policies, as discussed in the following section.

6.2. Policies supporting the adoption of city hubs

Since the actors tend to regard the city hub as attractive only after using it (Akgün et al., 2020), the public authority perspective is crucial to subsidize at least the first implementation phase of the city hubs (as assumed in this paper). Moreover, Akgün et al. (2020) mention that the public actors involved in city hub projects should be able to show the LSPs that they can obtain benefits by using the city hub service. Our model can help show these benefits to all actors involved in the system.

Furthermore, Akgün et al. (2020) suggests that the public sector should provide strong support even after the startup phase by forcing LSPs to use the city hubs. There are different ways of achieving enforcement. One approach could be applying traffic restrictions to all LSPs except city hub users. An example of such an approach is the CityPorto Padova, where only the city hub vans are allowed to use the dedicated lanes of buses and taxis and have no time windows for loading/unloading in the ZTL (Limited Traffic Zone) (Leonardi et al., 2014). Moreover, Heeswijk et al. (2019) mention policies, such as access time restrictions and zone-access fees, that could help city hub implementation. The access time restriction could also be explored in the Stockholm case and might be a more successful policy than the environmental zone. However, analyzing how long the access time should be to persuade LSPs to use the city hub is needed. Heeswijk et al. (2019) mention that a 2-hour window is not enough for Copenhagen, and only windows up to 1h have the intended effect (i.e., convincing LSPs to adopt the city hub service). This type of analysis could be relevant for future work.

As described in Section 5.2, the environmental zone implemented in Stockholm aims not to reduce congestion but rather emissions. Before running the simulation, we hypothesized that implementing such a policy would help city hub adoption, also based on the literature evidence, e.g., Anand et al. (2021). However, this does not happen due to the low impact of vehicle cost change for medium and large LSPs. Moreover, it could lead to small-sized LSPs being driven out of the market because of the comparatively higher cost of delivering to the area than for medium and large LSPs. This is an unintended consequence of this policy that our modeling simulation highlights. The simulation results by Anand et al. (2021) test a delivery cap and price policy combined with a subsidy for a city hub and show that this policy could positively influence the use of city hubs, ensuring financial viability. The results presented in this work go against these results. This contrast may be because Anand et al. (2021) did not consider that LSPs could shift toward electric vehicles instead of paying the carbon credit points.

6.3. Theoretical implications of using system dynamics in urban logistics

One of the contributions of this research is the use of system dynamics in urban logistics. To the best of our knowledge, this paper presents the first application of system dynamics to the problem of city hubs in urban logistics. As mentioned in Section 2.2, the system dynamics model of Hu et al. (2022) can be considered similar to the one in our study but applied to the case of Underground Logistic Systems (ULS). Hu et al. (2022) model different actors involved in a ULS, such as LSPs, ULS operators and infrastructure actors. Moreover, they present the results of scenarios with varying values for public sector engagement and market acceptance of ULS schemes. Our paper adopts a similar approach, but we study city hubs instead of ULS.

A contribution of our work is that the fee dynamics are modeled assuming that the hub operator actively adjust the fee for their service to reach their profit goal. However, other hub operator pricing strategies could be used as well, such as considering competition and profit maximization (instead of profit goal) (Yan et al., 2019) or including a balance between service quality and fee (Kituyi et al., 2012). These different strategies would impact the dynamics of the system and, in turn, the model's results. Moreover, our model assumes that the pricing should change only every fixed period equal to ADJUSTMENT TIME FOR FEES. A change in this assumption would bring a higher or lower fee, which would, in turn, speed up or slow down the adoption of the service, but not change the long-term results.

When studying applicability of the model to other cases, the size of the area and the demand to the area must be carefully considered. As noted in Janjevic and Ndiaye (2017), the size of the actors plays an important role in the attractiveness of the service and in the impact of different strategies. The studied area is relatively small in geographical size, while it has a high number of receivers. Therefore, the applicability of the model is higher in areas with similar number of receivers per kilometer squared or similar number of deliveries per kilometer squared, as the dynamics of the system could change with different density of receivers or deliveries. Moreover, the LSPs and receivers have been divided into large, medium and small depending on the number of deliveries made or received respectively, following the division done within the Arenastaden case study. This could have been done in a different way (i.e., choosing different market shares for when we consider an actor to be large, medium or small). However, we believe that the behavior of the LSPs can be generalized. Therefore, the model can be used in areas with similar size, demand and market shares of different actors, by adjusting the input data. Finally, the model is used in this paper to analyze the dynamics of a single area. Therefore, it is not meant to be used to analyze the overall dynamics at an urban level (e.g., the entire city of Stockholm). Models analyzing each area could be combined to get a bigger picture, but additional dynamics at a higher urban level might need to be added, such as dynamics considering interactions between the areas.

6.4. Limitations and future work

This paper considers three actors: LSPs, receivers, and the hub operator. Moreover, the policy perspective is also discussed. Another actor that plays a role in the urban logistics context is the shippers of the goods. Shippers have not been explicitly considered in this paper, but could be a relevant future addition to the model. This study does not take into account other possible revenue streams that are related to time savings when LSPs deliver to the city hub. The actors could serve other customers and generate additional revenue, as noted in Janjevic and Ndiaye (2017). Furthermore, this study considers the dynamics and interactions between the hub operator and LSPs and between the hub operator and receivers. However, the direct and indirect interdependencies of behavior between LSPs and receivers are not considered. For example, LSPs and receivers could have shared and aligned sustainability goals that could lead them to join the hub. This is considered as an avenue for future work.

Due to limited data availability, the input variables (Table 2) are taken from different sources, such as the case study and previous literature and some of them result from assumptions. The data merging from heterogeneous sources and the assumptions made could provide a limitation to the results. However, the data is taken mainly from the case study and literature that presents key similarities to the case study, and most of the assumptions are tested either in the sensitivity analysis or in the definition of the different scenarios.

A few limitations come from the boundaries chosen for the development of the model. One of the assumptions in the model is that only considered emissions are emissions in the case study area. This assumption brings a limitation, as a life-cycle perspective on emissions would be more comprehensive and bring more system-level results. In Sweden, the electricity production mainly relies on nuclear, biofuel, waste and hydro (IEA, 2025). Therefore, the grid-related emissions are rarely discussed in the Swedish context. However, it is of core importance to acknowledge these emissions in other countries, and future work could include the life-cycle perspective in the model. Moreover, other key performance indicators could be selected to study the impacts of city hubs (e.g., the effect of electrification on the existing electrical grid and the need for charging infrastructure).

The different possible locations of the city hub are not considered, and how that would impact the efficiency of the system and the cost sustained by the various actors in the system. Instead of electric vehicles, cargo bikes could also be used, as pointed out by Elbert and Friedrich (2020). Cargo bikes can deliver items at lower costs. However, they can result in a lower fill rate and potentially need an adaptation in infrastructure. Finally, the hub operator could achieve extra profitability by including waste in their business model, as done in the case of Arenastaden and Älskade Stad in Stockholm (Älskade Stad, 2023). These additional dynamics and considerations could be relevant to be addressed in future work.

Building on the findings of this study, operations planning problems emerge as areas for future research. One example is the design of pricing strategies for receivers, such as developing dynamic pricing models that balance costs and revenue for both the hub and the receivers, potentially factoring in time savings, order frequency, or receiver density. Another avenue is optimizing the hub operator's resource allocation, such as scheduling deliveries or routing vehicles to minimize operational costs and maximize service efficiency (Simoni et al., 2018). Additionally, exploring the integration of dynamic pricing with location-based policies (e.g., time-restricted access or environmental zones) could offer further insights for policymakers. Finally, the role of other emerging technologies (such as autonomous trucks, side-walk delivery robots and drones) and innovations (such as Big Data Analytics) could play a role in the future of urban logistics (Zenezini et al., 2022). These technologies are not considered in the paper as they are still under development and not yet available in the market. They are highlighted here as they could be added as a delivery mode in the model and they could bring huge benefits to the economic perspective of city hubs, as one of the main costs to deliver in urban areas is the cost of the drivers. Analyzing such technologies with a system-level perspective could be a potential avenue for future work, since the socio-technical impacts of these new technologies is of key importance to the sustainability of future urban logistics systems.

7. Conclusion

This paper uses a system dynamics method to understand the conditions that lead to a sustainable city hub implementation and explore how different strategies and policies impact this implementation. The system dynamics method is suitable for urban logistics systems as these are complex and influenced by multiple actors' decisions. The perspectives of three actors are explored in this paper: the LSPs, the receivers and the hub operator. The method allows us to understand the dynamics of city hub implementation from the perspectives of these different actors and to model the adoption of the city hub service quantitatively. The key takeaways of this paper are the following.

- Our results demonstrate that the city hub is economically sustainable only if collaboration is achieved between LSPs and receivers, i.e., when LSPs and receivers share the operational cost of the hub by paying a hub fee.
- Even when collaboration between LSPs and receivers is achieved, the total system cost (including the total operational cost and fees paid by the receivers and LSPs) increases. The increase in total system cost indicates that achieving the economic sustainability of the city hub is difficult, as the operational benefits drawn from city hubs (i.e., lower cost of operations for the LSPs) do not cover the extra costs. Therefore, additional benefits must be identified and monetized, especially from the receivers' perspective.
- If collaboration between actors cannot be achieved, the public sector's involvement is crucial to achieving city hub adoption. However, implementing an environmental zone (limiting the types of vehicles entering the studied area to electric vehicles) is not expected to help city hub adoption, as the share of LSPs cost spent on vehicles is relatively low compared to salary cost and fuel cost. It could even lead to small-sized LSPs being driven out of the market in a specific area. Other policies should be considered to enhance city hub adoption, such as applying traffic restrictions to all LSPs except city hub adopters.
- System dynamics has proven to be a helpful method to study complex problems in the urban logistic context, especially when considering different actors' perspectives. The model can be used in areas with similar size, demand and market shares of different actors, by adjusting the input data.

The main contribution of this paper lies in identifying potential strategies and outcomes within the studied area and providing guidance for policymakers on viable policies for city hub implementation. Furthermore, the adaptable nature of the model enables its application to other case studies by adjusting the input data, thereby serving as a tool for analyzing similar problems in different geographical contexts. Moreover, the model has proven to be useful to identify unintended consequences of public policy (i.e., the exclusion of small logistic providers from the market when implementing an environmental zone). The main avenue for future work is further exploration of the receivers' perspective, including quantifying the benefits of receiving deliveries through the city hub scheme.

Authors contributions

CA: conceptualization, investigation, methodology, software, validation, writing - original draft, writing - reviewing and editing. GZ: conceptualization, methodology, writing - reviewing and editing, supervision. HG: conceptualization, investigation, writing - reviewing and editing, supervision. AP: conceptualization, methodology, writing - reviewing and editing, supervision, funding acquisition.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This research was funded by Sweden's Innovation Agency (Vinnova) within the FFI program under Grant number 2020-00565.

ORCID

Claudia Andruetto http://orcid.org/0000-0002-0575-5213
Anna Pernestål http://orcid.org/0000-0003-2011-6273

Data availability statement

The documentation of the model and the data that support the findings of this study are available from the corresponding author upon reasonable request.

References

Akgün, E. Z., Monios, J., & Fonzone, A. (2020). Supporting urban consolidation centres with urban freight transport policies: A comparative study of Scotland and Sweden. *International Journal of Logistics Research and Applications*, *23*(3), 291–310. https://doi.org/10.1080/13675567.2019.1679743

Älskade Stad. (2023). About Älskade Stad. Retrieved April 17, 2023, from https://www.alskadestad.se/about-alskade-stad/

Anand, N., van Duin, R., & Tavasszy, L. (2021). Carbon credits and urban freight consolidation: An experiment using agent based simulation. *Research in Transportation Economics*, *85*, 100797. https://doi.org/10.1016/j.retrec.2019.100797

Andruetto, C., Stenemo, E., & Pernestål, A. (2024). Towards sustainable urban logistics: Exploring the implementation of city hubs through system dynamics. *Transportation Research Interdisciplinary Perspectives*, *27*, 101204. https://doi.org/10.1016/j.trip.2024.101204

Basma, H., Rodríguez, F., Hildermeier, J., & Jahn, A. (2022, June). Electrifying last-mile delivery. A total cost of ownership comparison of NOVEMBER 2020 battery-electric and diesel trucks in Europe (Tech. rep.). International Council on Clean Transportation and Regulatory Assistance Project.

Björklund, M., & Johansson, H. (2018). Urban consolidation centre—A literature review, categorisation, and a future research agenda. *International Journal of Physical Distribution & Logistics Management*, *48*(8), 745–764. https://doi.org/10.1108/IJPDLM-01-2017-0050

Bosona, T. (2020). Urban freight last mile logistics—Challenges and opportunities to improve sustainability: A literature review. *Sustainability*, *12*(21), 8769. https://doi.org/10.3390/su12218769

Browne, M., Allen, J., & Woodburn, A. G. (2007). *The role of urban consolidation centres for different business sectors* [Paper presentation]. Conference Proceedings. Retrieved December 5, 2023, from https://westminsterresearch.westminster.ac.uk/item/91wyv/the-role-of-urban-consolidation-centres-for-different-business-sectors

Browne, M., Sweet, M., Woodburn, D. A., & Allen, J. (2005). *Urban freight consolidation centres final report* (Tech. rep.). Department for Transport.

Cagliano, A. C., Carlin, A., Mangano, G., & Rafele, C. (2017). Analyzing the diffusion of eco-friendly vans for urban freight distribution. *The International Journal of Logistics Management*, *28*(4), 1218–1242. https://doi.org/10.1108/IJLM-05-2016-0123 Very interesting models with the diffusion of low emission goods vehicles. Good to take for references about low emission vehicles.

Dong, J., Xu, Y., Hwang, B-g., Ren, R., & Chen, Z. (2019). The impact of underground logistics system on urban sustainable development: A system dynamics approach. *Sustainability*, *11*(5), 1223. https://doi.org/10.3390/su11051223

Drivkraft Sverige (2022). Utveckling av försäljningspris för bensin, dieselbränsle och etanol—per år. Retrieved November 1, 2023, from https://drivkraftsverige.se/fakta-statistik/priser/

Duin, R., Slabbekoorn, M., Tavasszy, L., & Quak, H. (2018). Identifying dominant stakeholder perspectives on urban freight policies: A q-analysis on urban consolidation centres in The Netherlands. *Transport*, *33*(4), 867–880. https://doi.org/10.3846/16484142.2017.1350996

Elbert, R., & Friedrich, C. (2020). Urban consolidation and cargo bikes: A simulation study. *Transportation Research Procedia*, *48*, 439–451. https://doi.org/10.1016/j.trpro.2020.08.051

Estrada, M., & Roca-Riu, M. (2017). Stakeholder's profitability of carrier-led consolidation strategies in urban goods distribution. *Transportation Research Part E: Logistics and Transportation Review*, *104*, 165–188. https://doi.org/10.1016/j.tre.2017.06.009

Friedrich, C., & Elbert, R. (2022). Adaptive large neighborhood search for vehicle routing problems with transshipment facilities arising in city logistics. *Computers & Operations Research*, *137*, 105491. https://doi.org/10.1016/j.cor.2021.105491

Gammelgaard, B., Andersen, C. B. G., & Aastrup, J. (2016). Value co-creation in the interface between city logistics provider and in-store processes. *Transportation Research Procedia*, *12*, 787–799. https://doi.org/10.1016/j.trpro.2016.02.032

Heeswijk, W., Larsen, R., & Larsen, A. (2019). An urban consolidation center in the city of Copenhagen: A simulation study. *International Journal of Sustainable Transportation*, *13*(9), 675–691. https://doi.org/10.1080/15568318.2018.1503380

Holguín-Veras, J., Amaya Leal, J., Sánchez-Diaz, I., Browne, M., & Wojtowicz, J. (2020a). State of the art and practice of urban freight management: Part I: Infrastructure, vehicle-related, and traffic operations. *Transportation Research Part A: Policy and Practice*, *137*, 360–382. https://doi.org/10.1016/j.tra.2018.10.037

Holguín-Veras, J., Amaya Leal, J., Sanchez-Diaz, I., Browne, M., & Wojtowicz, J. (2020b). State of the art and practice of urban freight management part II: Financial approaches, logistics, and demand management. *Transportation Research Part A: Policy and Practice*, *137*, 383–410. https://doi.org/10.1016/j.tra.2018.10.036

Hu, W., Dong, J., Hwang, B-g., Ren, R., Chen, Y., & Chen, Z. (2020). Using system dynamics to analyze the development of urban freight transportation system based on rail transit: A case study of Beijing. *Sustainable Cities and Society*, *53*, 101923. https://doi.org/10.1016/j.scs.2019.101923

Hu, W., Dong, J., Yuan, J., Ren, R., Chen, Z., & Cheng, H. (2022). Agent-based modeling approach for evaluating underground logistics system benefits and long-term development in megacities. *Journal of Management Science and Engineering*, *7*(2), 266–286. https://doi.org/10.1016/j.jmse.2021.10.002

IEA (2025, January 29). *Sweden - energy mix*. https://www.iea.org/countries/sweden

Isa, S. S., Lima, O. F., & Fioravanti, R. D. (2020). The Kaldor–Hicks criterion applied to economic evaluation of urban consolidation centers. *Transportation Research Procedia*, *48*, 416–427. https://doi.org/10.1016/j.trpro.2020.08.049

Iwan, S., Nürnberg, M., Jedliński, M., & Kijewska, K. (2021). Efficiency of light electric vehicles in last mile deliveries—Szczecin case study. *Sustainable Cities and Society*, *74*, 103167. https://doi.org/10.1016/j.scs.2021.103167

Janjevic, M., & Ndiaye, A. (2017). Investigating the financial viability of urban consolidation centre projects. *Research in Transportation Business & Management*, *24*, 101–113. https://doi.org/10.1016/j.rtbm.2017.05.001

Johansson, H., & Björklund, M. (2017). Urban consolidation centres: Retail stores' demands for UCC services. *International Journal of Physical Distribution & Logistics Management*, *47*(7), 646–662. https://doi.org/10.1108/IJPDLM-02-2017-0114

Katsela, K., & Pålsson, H. (2021). Viable business models for city logistics: Exploring the cost structure and the economy of scale in a

Swedish initiative. *Research in Transportation Economics*, *90*, 100857. https://doi.org/10.1016/j.retrec.2020.100857

Katsela, K., Güneş, Ş., Fried, T., Goodchild, A., & Browne, M. (2022). Defining urban freight microhubs: A case study analysis. *Sustainability*, *14*(1), 532. https://doi.org/10.3390/su14010532

Katsela, K., Pålsson, H., & Ivernå, J. (2022). Environmental impact and costs of externalities of using urban consolidation centres: A 24-hour observation study with modelling in four scenarios. *International Journal of Logistics Research and Applications*, *25*(12), 1542–1563. https://doi.org/10.1080/13675567.2021.1915261

Kin, B., Hopman, M., & Quak, H. (2021). Different charging strategies for electric vehicle fleets in urban freight transport. *Sustainability*, *13*(23), 13080. https://doi.org/10.3390/su132313080

Kin, B., Spoor, J., Verlinde, S., Macharis, C., & Van Woensel, T. (2018). Modelling alternative distribution set-ups for fragmented last mile transport: Towards more efficient and sustainable urban freight transport [urban freight transport; sustainability; megacities; modelling]. *Case Studies on Transport Policy*, *6*(1), 125–132. https://doi.org/10.1016/j.cstp.2017.11.009

Kituyi, G., Moya, M., Rwashana, A., & Rwashana, A. (2012). A system dynamics pricing model for stabilizing prices for telecommunication products and services in Uganda. *International Scientific Research Journal*, *1*, 7–14.

Konsumenternas Energimarknadsbyrå. (2023). Elkostnader. Retrieved October 24, 2023, from http://www.energimarknadsbyran.se/el/dina-avtal-och-kostnader/elkostnader/

Kunze, O., Wulfhorst, G., & Minner, S. (2016). Applying systems thinking to city logistics: A qualitative (and quantitative) approach to model interdependencies of decisions by various stakeholders and their impact on city logistics. *Transportation Research Procedia*, *12*, 692–706. Very thorough description of system variables but quite complex to understand. https://doi.org/10.1016/j.trpro.2016.02.022

Leonardi, J., Browne, M., Allen, J., Bohne, S., & Ruesch, M. (2014). Best practice factory for freight transport in Europe: Demonstrating how 'good' urban freight cases are improving business profit and public sectors benefits. *Procedia - Social and Behavioral Sciences*, *125*, 84–98. https://doi.org/10.1016/j.sbspro.2014.01.1458

Lindholm, M., & Behrends, S. (2012). Challenges in urban freight transport planning—A review in the Baltic Sea region. *Journal of Transport Geography*, *22*, 129–136. https://doi.org/10.1016/j.jtrangeo.2012.01.001

Malmgren, T. (2022). *Arena för transporteffektiv stadsmiljö—Goda exempel som ger ökad klimatnytta i närtid* (Tech. rep.). Swedish Transport Administration.

McLeod, S., & Curtis, C. (2020). Understanding and planning for freight movement in cities: Practices and challenges. *Planning Practice & Research*, *35*(2), 201–219. https://doi.org/10.1080/02697459.2020.1732660

MDS. (2012, April). *DG move European commission: Study on urban freight transport* (Tech. rep.). MDS.

Melkonyan, A., Gruchmann, T., Lohmar, F., Kamath, V., & Spinler, S. (2020). Sustainability assessment of last-mile logistics and distribution strategies: The case of local food networks. *International Journal of Production Economics*, *228*, 107746. https://doi.org/10.1016/j.ijpe.2020.107746

Nataraj, S., Ferone, D., Quintero-Araujo, C., Juan, A., & Festa, P. (2019). Consolidation centers in city logistics: A cooperative approach based on the location routing problem. *International Journal of Industrial Engineering Computations*, *10*(3), 393–404. https://doi.org/10.5267/j.ijiec.2019.1.001

Nathanail, E., Terzakis, T., & Zerzis, D. (2020). Estimating the sustainability impacts of an urban consolidation center in a medium-sized city. In I. Kabashkin, I. Yatskiv, & O. Prentkovskis (Eds.), *Reliability and statistics in transportation and communication* (pp. 277–286). Springer International Publishing. https://doi.org/10.1007/978-3-030-44610-9_28

Nenni, M. E., Sforza, A., & Sterle, C. (2019). Sustainability-based review of urban freight models. *Soft Computing*, *23*(9), 2899–2909. https://doi.org/10.1007/s00500-019-03786-x

Nocera, S., & Cavallaro, F. (2017). A two-step method to evaluate the well-to-wheel carbon efficiency of urban consolidation centres. *Research in Transportation Economics*, *65*, 44–55. https://doi.org/10.1016/j.retrec.2017.04.001

Noll, B., del Val, S., Schmidt, T. S., & Steffen, B. (2022). Analyzing the competitiveness of low-carbon drive-technologies in road-freight: A total cost of ownership analysis in Europe. *Applied Energy*, *306*, 118079. https://doi.org/10.1016/j.apenergy.2021.118079

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. https://doi.org/10.1016/j.tranpol.2015.08.005

Paddeu, D. (2017). The Bristol-Bath urban freight consolidation centre from the perspective of its users. *Case Studies on Transport Policy*, *5*(3), 483–491. https://doi.org/10.1016/j.cstp.2017.06.001

Paddeu, D. (2021). The five attribute performance assessment (FAPA) model to evaluate the performance of an urban consolidation centre. *Research in Transportation Economics*, *90*, 101065. https://doi.org/10.1016/j.retrec.2021.101065

Paddeu, D., & Parkhurst, G. (2020). The potential for automation to transform urban deliveries: Drivers, barriers and policy priorities. *Advances in Transport Policy and Planning*, *5*, 291–314. https://doi.org/10.1016/bs.atpp.2020.01.003 https://linkinghub.elsevier.com/retrieve/pii/S2543000920300032

Paddeu, D., Parkhurst, G., Fancello, G., Fadda, P., & Ricci, M. (2018). Multi-stakeholder collaboration in urban freight consolidation schemes: Drivers and barriers to implementation. *Transport*, *33*(4), 913–929. https://doi.org/10.3846/transport.2018.6593

Rabe, M., Klueter, A., & Wuttke, A. (2018). Evaluating the consolidation of distribution flows using a discrete event supply chain simulation tool: Application to a case study in Greece. In *2018 Winter Simulation Conference (WSC)* (pp. 2815–2826). https://doi.org/10.1109/WSC.2018.8632266

Ranieri, L., Digiesi, S., Silvestri, B., & Roccotelli, M. (2018). A review of last mile logistics innovations in an externalities cost reduction vision. *Sustainability*, *10*(3), 782. https://doi.org/10.3390/su10030782

SCB (2023). Electricity prices and electricity contracts. Retrieved October 24, 2023, from https://www.scb.se/en0301-en

Schonewille, G. A. (2015, February). *Calculation of Transport Cost for Freight Carriers on the Last Mile* [Doctoral dissertation]. Delft University of Technology.

Sheth, M., Butrina, P., Goodchild, A., & McCormack, E. (2019). Measuring delivery route cost trade-offs between electric-assist cargo bicycles and delivery trucks in dense urban areas. *European Transport Research Review*, *11*(1), 11. https://doi.org/10.1186/s12544-019-0349-5

Shojaei, M. H. S., Fakhrmoosavi, F., Zockaie, A., Ghamami, M., Mittal, A., & Fishelson, J. (2022). Sustainable transportation networks incorporating green modes for urban freight delivery. *Journal of Transportation Engineering, Part A: Systems*, *148*(6), 04022028. https://doi.org/10.1061/JTEPBS.0000669

Simoni, M. D., Bujanovic, P., Boyles, S. D., & Kutanoglu, E. (2018). Urban consolidation solutions for parcel delivery considering location, fleet and route choice. *Case Studies on Transport Policy*, *6*(1), 112–124. https://doi.org/10.1016/j.cstp.2017.11.002

Sterman, J. D. (2000). *Business dynamics: Systems thinking and modeling for a complex world*. Irwin/McGraw-Hill. Retrieved March 23, 2021, from http://web.mit.edu/jsterman/www/BusDyn2.html

Sterman, J. D. (2001). System dynamics modeling - tools for learning in a complex world. *California Management Review*, *43*(4), 8–25. https://www.researchgate.net/publication/3228150_System_dynamics_modeling_Tools_for_learning_in_a_complex_world https://doi.org/10.2307/41166098

Stockholms stad (2020). *Vision 2040—Möjligheternas Stockholm* (Vision). Stockholms stad. https://start.stockholm/om-stockholms-stad/stadens-vision/

Thaller, C., Clausen, U., & Kampmann, R. (2016). System dynamics based, microscopic freight transport simulation for urban areas. In

U. Clausen, H. Friedrich, C. Thaller, & C. Geiger (Eds.), *Commercial transport* (pp. 55–72). Springer International Publishing.

Trafikkontoret (2024). Konsekvensanalys miljözon klass 3 i ett område i city. http://insynsverige.se/documentHandler.ashx?did=2045659

van Rooijen, T., & Quak, H. (2010). Local impacts of a new urban consolidation centre—The case of Binnenstadservice.nl. *Procedia - Social and Behavioral Sciences*, *2*(3), 5967–5979. https://doi.org/10.1016/j.sbspro.2010.04.011

Veličković, M., Stojanović, Đ., Nikoličić, S., & Maslarić, M. (2018). Different urban consolidation centre scenarios: Impact on external costs of last-mile deliveries. *Transport*, *33*(4), 948–958. https://doi.org/10.3846/16484142.2017.1350995

Wasiak, M., Jacyna, M., Lewczuk, K., & Szczepański, E. (2017). The method for evaluation of efficiency of the concept of centrally managed distribution in cities. *Transport*, *32*(4), 348–357. https://doi.org/10.3846/16484142.2017.1345005

Xu, Y., Dong, J., Ren, R., Yang, K., & Chen, Z. (2022). The impact of metro-based underground logistics system on city logistics performance under covid-19 epidemic: A case study of Wuhan, China. *Transport Policy*, *116*, 81–95. https://doi.org/10.1016/j.tranpol.2021.10.020

Yan, Q., Zhou, S., Zhang, X., & Li, Y. (2019). A system dynamics model of online stores' sales: Positive and negative e-WOM and promotion perspective. *Sustainability*, *11*(21), 6045. https://doi.org/10.3390/su11216045

Zenezini, G., Mangano, G., & De Marco, A. (2022). Experts' opinions about lasting innovative technologies in city logistics. *Research in Transportation Business & Management*, *45*, 100865. https://doi.org/10.1016/j.rtbm.2022.100865