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A simulative assessment of collaborative last mile delivery solutions

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Abstract

Collaborative last mile solutions, such as the collaborative use of parcel lockers, jointly used logistics facilities in inner-city area, and white-label delivery play an increasing role to alleviate inefficiencies particularly caused by failed home delivery attempts and generated externalities associated with last mile deliveries. However, there is limited research on the impacts of collaborative delivery approaches in last mile logistics. Therefore, the objective of this paper is to assess the impacts of collaborative delivery solutions on freight transport, transport costs and emissions. For this purpose, a synthetic world for the City of Hamburg, Germany, has been built up focusing on the parcel market with respectively parcel service providers (PSP) as well as their private and commercial customers. Based on this, a reference scenario and four collaborative distribution scenarios (white-label PSP – direct delivery, white-label PSP – collaborative use of parcel stations, collaborative use of micro-depots, white-label PSP – collaborative use of micro-depots and vehicles used) are developed which are simulated by the microscopic agent-based transport simulation *MATSim* and the linked route optimization *Jsprit*. Results strongly indicate that positive transport-related, business and environmental impacts could be achieved through the implementation of collaborative delivery solutions.

Keywords: collaborative last mile solutions; parcel lockers; micro-depot; white-label delivery; last mile delivery; microscopic transport simulation

1. Introduction

The continually rising E-commerce deliveries is dominated by the ongoing digitalisation which enables faster freight transport and higher service quality. These trends lead to new business models and delivery concepts that ensure

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parcels being delivered quickly and reliably to the customers. The major impact of these trends on urban logistics is the increase in direct home deliveries of small-sized frequent shipments generating a higher number of delivery vehicles driving and stopping in urban areas, which significantly increase congestion, accidents and emissions in cities (Liu, Wang, & Susilo, 2019). Therefore, researchers, decision-makers and practitioners intend to find operational solutions and innovations in last mile city logistics in order to make the urban transport system as a whole more sustainable (Buerklen, Schuete & Rudolph, 2023; Muñuzuri, Larrañeta, Onieva, & Cortés, 2005; Patier & Browne, 2010).

In order to improve the efficiency and effectiveness of urban logistics systems and, in particular, to ensure a successful delivery attempt of shipments to private customers, automated parcel stations (or parcel lockers) as well as parcel shops (e.g. convenience stores, retailers) can be implemented (McKinnon, Wang, Potter, & Edwards, 2015; Vural & Aktepe, 2021). These can be used by the private customers to pick up and/or to return their parcels (Vural & Aktepe, 2021). Furthermore, such locations can be used collaboratively by all parcel service providers or only by one particular parcel service provider.

Another approach that allows to make last mile delivery operations more sustainable is the collaborative use of designated logistics space, such as distribution centers or micro-depots in inner-city areas. These transshipment and consolidation facilities are usually combined with the use of smaller and environmentally friendlier delivery vehicles, such as electrically assisted cargo bikes or delivery vans. In addition, the establishment of a white-label operator starting from these facilities can alleviate the inefficiencies and externalities in last mile city logistics. Thereby, it is expected that the consolidation of loads of various parcel service providers leads to fewer trips and number of delivery vehicles in urban areas due to improved vehicle capacity utilization (Buerklen, Schuete & Rudolph, 2023).

Indeed, current research on collaborative distribution solutions indicates that they can significantly reduce distance-based transport costs and environmental costs through a reduction in vehicle usage, improved volume capacity utilization and mileage performed (see e.g. Hribernik, Zero, Kummer & Herold, 2020; Juan, Faulin, Pérez-Bernabeu & Jozefowiez, 2014; Juan et al., 2016; Montoya-Torres, Muñoz-Villamizar & Vega-Mejía, 2016; Quak, 2012; Quak, Nesterova & van Rooijen, 2016; Thompson & Hassall, 2012; Verdonck, Caris, Ramaekers & Janssens, 2013). More specifically, Hribernik, Zero, Kummer and Herold (2020) highlight that collaboration among PSP can result in significant benefits. Juan, Faulin, Pérez-Bernabeu and Jozefowiez (2014) and Juan et al. (2016) demonstrate a reduction in distance-based transport costs by up to 16%. Verdonck, Caris, Ramaekers & Janssens (2013) explore a 24% decrease in environmental costs, and Quak, Nesterova and van Rooijen (2016) as well as Quak (2012) show a 25% increase in volume capacity utilization for cooperating partners. Thompson and Hassall (2020) use a hypothetical model of urban distribution comparing the performance of independent and collaborative networks, finding that the collaborative system could reduce transport distances by approximately 70% and the number of vehicles required by 25-50%.

However, collaborative last mile delivery concepts applicable for PSP have not been investigated and compared with each other in the context of one single case study as an ex-ante analysis, although the current state of research focusing on collaborative urban logistics modelling and simulation highlights the need for urban logistics models that include collaborative last mile delivery solutions in order to gain more knowledge of the potential implications of collaborative last mile delivery solutions in terms of sustainability and efficiency (Bean & Joubert, 2021; Gonzalez-Feliu & Salanova, 2012). In particular, white label scenarios have not yet been considered and provide a research gap.

Hence, this paper aims to set up a simulation study for an ex-ante analysis in order to investigate to what extent different collaborative last mile delivery solutions (e.g. collaborative use of parcel stations, designated logistic space, white-label operator) comparatively contribute to a more sustainable urban freight transport and what impacts can comparatively be observed on relevant parameters regarding efficiency (e.g. transport costs, number of stops, transport time, etc.). Therefore, the microscopic agent-based transport simulation *MATSim* (Horni, Nagel & Axhausen, 2016) and the linked route optimization *Jsprit* (Schröder et al., 2012) are used for which a synthetic world for the City of Hamburg has been built up focusing on the parcel market with respectively parcel service providers as well as their private and commercial customers.

The paper is organized as follows: In Section 2 the methodical procedure of the simulation will be presented and the main input needed to perform the simulation will be described. In Section 3 the results of the simulation will be summarized, which is followed by the discussion of the simulation results and recommendations for action for transport policy and urban logistics (Section 4). Section 5 will conclude with remarks and suggestions for possible future research.

2. Methodology

This section describes the methodical procedure of the simulation, which is used to assess collaborative last mile delivery solutions in the City of Hamburg, namely the collaborative use of parcel lockers, collaborative use of logistics space in inner-city areas and white-label delivery. Moreover, the purpose of using a simulation tool in this work is to explain the phenomena emerging from the actions of carriers, which, in this study, correspond to parcel delivery vehicle drivers making deliveries in the City of Hamburg. Furthermore, in this section, the input data used and the preparation of these to build up the synthetic world for MATSim and to parametrize the scenarios developed will be presented and described in detail.

Models used for simulation and optimization

For this study, the microscopic agent-based transport simulation MATSim (Horni, Nagel & Axhausen, 2016) and the linked route optimization Jsprit (Schröder et al., 2012) are used for simulating and optimizing the urban freight transport observed and to assess the impacts of the selected urban logistics measures. MATSim is used to assign the vehicle routes to the infrastructure, simulate the single routes at the infrastructure within a day and illustrate the travel behavior of the drivers in urban freight transport at the infrastructural level. In addition, routes can be optimized by Jsprit. As a result, a typical day is simulated in MATSim/Jsprit. When optimizing the transport costs using Jsprit, the following constraints are applied: (i) The delivery trips to the customers start at the respective distribution center. (ii) The delivery quantities to customers are known in advance. (iii) The delivery times of the deliveries can be limited by time windows. (iv) Each carrier is assigned a fleet consisting of different vehicle types. The vehicle types differ in terms of capacity and costs. (v) A maximum of one route per day can be assigned to a vehicle.

There are three modelling steps to be carried out. In the first step, the initial simulation world is built up by creating agents, locations and network infrastructure using object-oriented concepts of the java programming language. For this purpose, the infrastructure network, freight demand, georeferenced locations and characteristics of the parcel service providers, as well as the private and commercial customers are processed and stored as input files for the simulation. The second step is the actual simulation of the model. First of all, the agents' tour plans are generated using Jsprit and executed in the MATSim mobsim module. To generate tour plans, Jsprit uses its routing problem solver, which involves an iterative scoring and replanning function, to arrive at a solution. Thus, the mobsim execution is performed without the native MATSim scoring and replanning function because the tour plans from Jsprit are considered final. Additionally, the MATSim execution module allows for the direct simulation of tour plans on a digitalized real network. In the simulation, each carrier agent represents a parcel service provider with a set of vehicles, a depot and a delivery plan. The agents' plans contain a tour schedule for each delivery vehicle, including planned pick-up/delivery, arrival times at the delivery locations (e.g. private and commercial customers) and a route through the transport network. When a simulation scenario is initialized, the carriers build a time schedule for each of their delivery vehicles, including a route through the transport network, with delivery activities corresponding to their plans. Subsequently, all the information on the carriers' activities at a specific time is summarized in an event file. In a further step, the resulting event file is processed for analysis of relevant indicators.

In general, the methodical procedure for performing the simulation scenarios contains two main components of the author's tasks. Firstly, the parameters adjustment, which is based on the different data, including all assumptions made, and on the input files needed to initialize simulation scenarios. Secondly, the analysis of the simulation results that are summarized in the carriers' event file leading to decide whether results make sense or not so that different scenarios can be generated and assessed. Therefore, in order to estimate the volume of parcels delivered to private and commercial customers, demand estimation methods have been employed including a synthetic population dataset which was derived using accessible city population data and aggregated parcel demand from studies on the courier, express and parcel industry. Furthermore, Monte Carlo simulation technique has been applied for the disaggregation of the parcel demand and generation of a provider-customer distribution matrix. Subsequently, the deployed microscopic agent-based transport simulation *MATSim* and the linked route optimization *Jsprit* can simulate parcel distribution on the road network infrastructure of the City of Hamburg.

Parametrizing the model

For the purpose of modelling and simulation, data regarding the network infrastructure as well as locations and characteristics of parcel service providers and their private and commercial clients in Table 1 form the main input dataset and has been collected and processed beforehand. The methodological procedure for collecting and preparing the data to set up the scenarios is described in detail in Thaller (2018) for the case study Berlin. The infrastructure network for the City of Hamburg from OpenStreetMap (2020) is used, in which every edge of the network is defined (e.g. length, maximum velocity, capacity and number of lanes). In order to optimize and simulate delivery routes and the actual freight tours, the digital network infrastructure of the City of Hamburg extracted from OpenStreetMap has been converted to a suitable format for the simulation using the *MATSim* OsmNetworkReader utility.

The daily freight demand (parcel units) of city residents as private clients is calculated based on the data sources BIEK (2020), Manner-Romberg, Kille & Müller-Steinfahrt (2015) as well as Statistics Agency for Hamburg and Schleswig-Holstein (2020). BIEK (2020) provides a CEP-index B2C – number of parcels per inhabitants or freight demand per person per year fd_p. This is used to calculate the total number of parcels of private clients per year FD_p: $fd_p\ P$, whereby P is the total population of Hamburg. Afterwards, the freight demand per day: FD_p/wd is derived, whereby wd is working days per year, including Saturdays. To simulate delivery destinations, a synthetic population dataset is generated using the population data and building blocks census data for the City of Hamburg (Statistics Agency for Hamburg and Schleswig-Holstein 2020). In this case, private customers (B2C) are private households, for which information on the number of private persons with their corresponding socio demographic characteristics differentiated according to nine age cohorts is provided per statistical area. The commercial freight demand per day is also estimated based on the data sources BIEK (2020) and Statistics Agency for Hamburg and Schleswig-Holstein (2020). The CEP-index B2B – number of parcels per one million € of gross domestic product (GDP) per year (BIEK, 2020) is multiplied by the GDP of Hamburg in total to calculate the parcels to commercial clients for this study area in total. Then, the commercial freight demand per typical working day for 2020 is derived. The locations of the commercial customers (B2B) are extracted from the data base OpenStreetMap (2020). According to Thaller (2018, 2019), Thaller et al. (2019) and Zhang, Matteis, Thaller & Liedtke (2018), retailers, gastronomy and the service sector as well as public institutions and universities are considered as attractors of parcels. For this purpose, three data sets of OpenStreetMap (2020) (i.e. files concerning land use, buildings, points) are used to identify these companies and institutions. Especially the selected companies were classified according to the German Classification of Economic Activities (2008) – WZ 2008 (Destatis 2020).

The addresses of the distribution centers of parcel service providers in the City of Hamburg were identified by using the Internet platform Paketda (2020). In total, 17 distribution centers (9 DHL, 3 DPD, 2 Hermes, 3 UPS) were prepared and georeferenced for the synthetic world.

In order to simulate micro-depots defined by Janjevic and Ndiaye (2014) as "*logistics facilities located inside or close by the delivery area, in which logistics service provider can (un)load, sort, store, and deliver parcels from it to the end-receiver*", potential locations have been first defined. For this study, it is assumed that potential locations of micro-depots would include areas in front of filling stations, supermarkets, department stores, post branches and parcel stations. Filling stations, supermarkets and department stores were extracted using OpenStreetMap (2020). The addresses of post branches and parcel stations are identified by means of an extensive internet research using several sources (i.e. Figiel Interactive (2020), Reinhardt Internet Media GbR (2020), DPD iloxx Service GmbH (2020)). In this context, also locations of parcel shops were collected. Afterwards, the locations were georeferenced for the synthetic world. Following the described survey approach, 843 potential micro-depot locations were identified, consisting of 159 filling stations, 453 supermarkets, 22 department stores, 119 post branches and 90 parcel stations.

The characteristics of the parcel service providers are shown in **Fig. 1**, which includes geographic coordinates of logistics nodes.

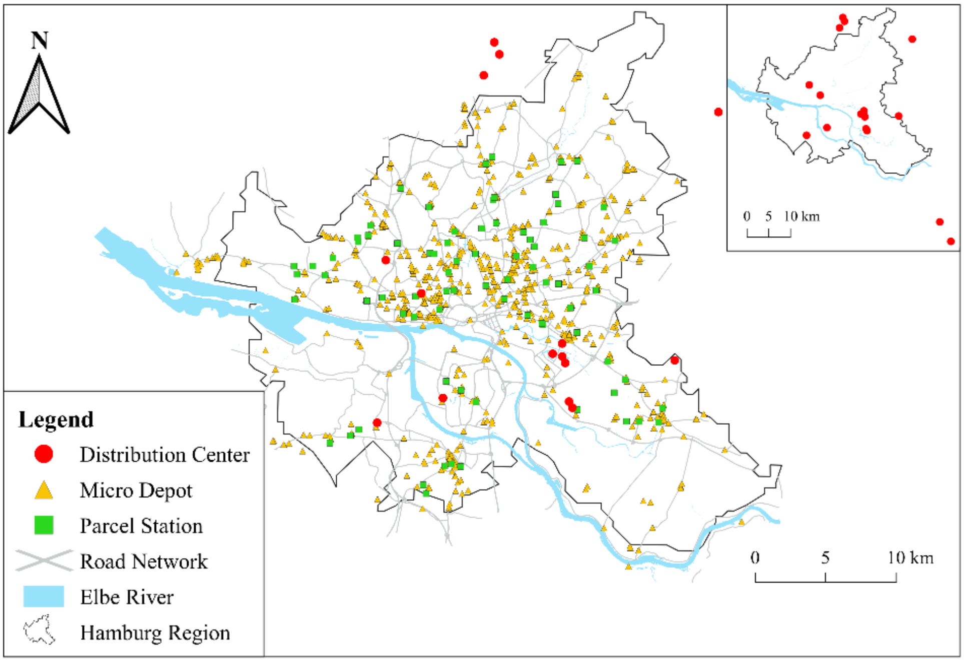

Fig. 1. Map of Hamburg showing facilities of parcel service providers

Vehicle specifications for the fleet of service providers is derived from characteristics of the diesel-driven truck 3.5t permissible total weight (ptw) defined for this study. Furthermore, transport costs, including fixed, variable and personnel costs are determined using total cost of ownership (TCO) calculations. In order to derive the costs by TCO calculations, several data sources are used (BGL (2020), ETM (2017), DAT Group (2018), Mehlhart, Merz, Akkermans & Jordal-Joergensen (2011), MWV (2018), Schulz (2017)). The TCO calculation according to Wittenbrink (2014) is applied. Characteristics for the cargo bikes used for the further collaborative scenarios are according to Zhang, Matteis, Thaller & Liedtke (2018) and Fahrrad-XXL GmbH (2018).

In addition, emission conversion factors are used to estimate the quantity of emissions (i.e., environmental impacts) the freight vehicles generate when carrying out the deliveries. Based on data for fuel consumption per km and conversion factors per km differentiated for different vehicle types of the handbook emission factors of road freight transport (HBEFA) according to Infras AG (2022), the total fuel consumption and total emissions (e.g. CO_2) are computed after the simulation. The simulation results concerning road mileage performed per vehicle type is multiplied by these factors.

Information on the detailed preparation of the input data can also be found in Thaller (2018) where the parcel market for Berlin was already built up for MATSim and Jsprit. **Table 1** summarizes the input data and corresponding references.

Table 1. Input data values and sources

Data	Value	Compiled values from
Total freight demand (B2C)	118,367 parcels	BIEK (2020), Manner-Romberg, Kille & Müller-Steinfahrt (2015), Statistics Agency for Hamburg and Schleswig-Holstein (2020)
Total freight demand (B2B)	229,509 parcels	BIEK (2020), Statistics Agency for Hamburg and Schleswig-Holstein (2020)
Distribution centers	17 locations	Paketda (2020)
Parcel station locations	90 stations	Figiel Interactive (2020), Reinhardt Internet Media GbR (2020), DPD iloxx Service GmbH (2020)
Potential micro-depot locations	843 depots	Figiel Interactive (2020), Reinhardt Internet Media GbR (2020), DPD iloxx Service GmbH

Data	Value	Compiled values from
		(2020), OpenStreetMap (2020)
Road infrastructure network	-	OpenStreetMap (2020)
Delivery time window (B2C)	08:00 - 22:00	Thaller (2018)
Delivery time window (B2B)	06:00 - 12:00	Thaller (2018)
Characteristics of truck 3.5t ptw, e.g. truck capacity	160 parcels	Thaller (2018), BGL (2020), ETM (2017), DAT Group (2018), Mehlhart, Merz, Akkermans & Jordal-Joergensen (2011), MWV (2018), Schulz (2017), Wittenbrink (2014)
Characteristics of cargo bike, e.g. capacity	35 parcels	Zhang, Matteis, Thaller & Liedtke (2018), Fahrrad-XXL GmbH (2018)

Scenario development

In the following, the four scenarios developed with focus on different collaborative distribution approaches for the City of Hamburg will be described besides the reference scenario which shows the status quo. The aim is to examine the effects of these collaborative measures under controlled conditions – according to the ceteris paribus principle. The authors ensure that the scenarios build on one another and therefore enable ceteris paribus. A visualization of these scenarios will be presented in **Fig. 2**.

2.3.1. Reference scenario

The reference scenario serves as a benchmark, representing the current state of practice in the selected study area City of Hamburg for the analysis year 2020. Here, the parcels of private (private households, B2C) and commercial customers (B2B) are delivered by the parcel service providers by means of diesel-driven trucks 3.5 t ptw. Deliveries to both private and commercial customers are made directly from the distribution center closest to them, within scheduled time windows (see **Table 1**). Each of the five most important parcel service providers (PSP) in Germany, i.e. DHL, Hermes, UPS, DPD, GLS, is represented individually in the model with its own market share, corresponding shipments as well as its own fleet and personnel to deliver parcels to its customers. PSPs also maintain their own infrastructure, including distribution centers and parcel shops. The market share by volume of parcel service providers is assumed based on the German parcel shipping index by Pitney Bowes (2021) for the year 2020. We assume a consistent total transport cost optimization of each individual PSP separately.

2.3.2. Scenario 1: White-label parcel service provider – Direct delivery

In this scenario, it is assumed that a white-label parcel service provider delivers the parcels to the customers in the investigation area. All other parameters (i.e. parcel demand, transport costs, location of logistics facilities and vehicle type) remain unchanged. In our study, the white-label PSP is defined as a monopolist who have complete control of the last mile delivery market and therefore is responsible for delivering the parcels for the whole city. The responsibility of the white-label PSP begins with the transshipment of the parcels from the main run to last mile at the distribution centers. Similar to the reference scenario, both private and commercial customers are delivered directly from the nearest distribution center by the white-label PSP by means of diesel-driven trucks 3,5t ptw.

2.3.3. Scenario 2: White-label parcel service provider – Collaborative use of parcel stations

Scenario 2 is similar to Scenario 1. The difference to Scenario 1 is that 100% of private customers use the delivery option parcel station. The parcel stations are delivered from the nearest distribution center by diesel-driven trucks 3.5t ptw. Parcels delivered to parcel stations can be retrieved by customers at any time. In this scenario, we assume the maximum capacity of each parcel station to be 76 parcels (DVZ 2010). If a parcel station is already at full capacity, the parcels are delivered to the nearest post office branch and made available for pick-up. A white-label parcel service provider is still responsible for parcel deliveries for the whole city.

2.3.4. Scenario 3: Collaborative use of micro-depots – Share of dedicated space for logistics purposes

This scenario is again similar to the reference scenario. The PSPs retain their market shares and logistics facilities. They also maintain their own vehicle fleet and personnel. However, the significant difference here lies in the parcel distribution for private customers. Instead of direct delivery from distribution centers to homes of private customers, the PSPs carry out a two-step distribution via micro-depots to deliver the private customers. In the first step, the requested parcel units are distributed from the distribution center to micro-depots by means of diesel-driven trucks 3.5t ptw. In the second step, parcel units, destined for private customers, are delivered from their nearest micro-depot at specified time windows, using electrified cargo bikes. The areas of the established micro-depots are shared and each PSP can access these micro-depots. Additionally, it is assumed that all private customers choose the home delivery option. Parcels intended for commercial customers are delivered directly from the nearest distribution center. For this scenario, 843 potential locations for micro-depots are considered. These include actual locations of parcel stations and parking areas in front of supermarkets, shopping centers and petrol stations.

2.3.5. Scenario 4: White-label parcel service provider – Collaborative use of micro-depots and vehicles used

This scenario is similar to Scenario 3, but with a white-label PSP operating in the City of Hamburg.

Fig. 2 shows the illustration of the distribution chain on the last mile and the assignment of the parcels to different PSPs or only one white-label PSP.

An overview of the input parameters (i.e. number of parcels delivered per day, preferred time windows for the delivery, stopping time, characteristics of the delivery vehicles used for the delivery process) for the presented scenarios is presented in **Appendices A** and **B**.

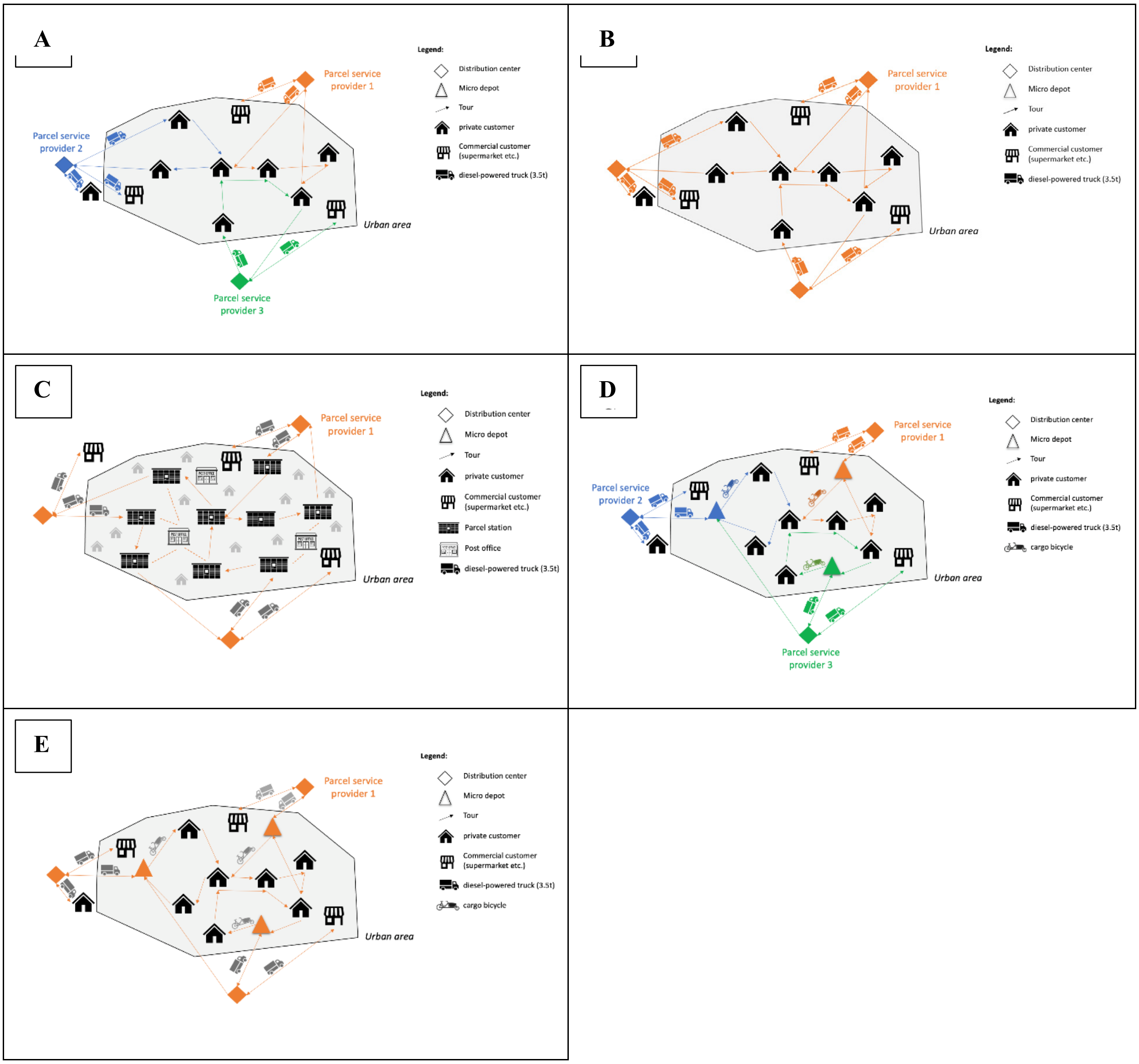

Fig. 2. Reference scenario (A), Scenario 1 (B), Scenario 2 (C), Scenario 3 (D), Scenario 4 (E) (Own diagrams)

4. Results

In the following, the simulation results for the scenarios 1-4 focusing on collaborative distribution solutions in last mile logistics applied for the parcel market in the City of Hamburg are shown in comparison to the reference scenario. We show transport-related impacts (e.g. freight transport demand, mileage performed), impacts on transport costs and ecological key figures (e.g. CO_2-emissions).

Transport-related impacts

Based on the simulation results recorded for the reference scenario, a total of 2,365 tours are carried out by 1,335 diesel-driven trucks 3.5t ptw within a typical day in the City of Hamburg. In Scenario 1, there are 1.9% fewer tours and 17.9% fewer diesel trucks than in the reference scenario. In Scenario 2, 2.2% less tours are conducted and 61.9% less diesel trucks are deployed. In Scenario 3, 228% more tours are carried out resulting in 48.7% fewer diesel trucks deployed and 714 cargo bikes used. In Scenario 4, a 156.8% increase in tours is recorded, translating to 59.4% reduction in diesel trucks used and 604 cargo bikes used (see **Fig. 3**). In comparison to the reference scenario, only scenarios with a two-step distribution process record an increase in the number of tours performed. These results indicate that more trips are required for a two-step distribution with cargo bikes due to their lower capacity, compared to trucks 3.5t ptw. Nonetheless, the results demonstrate remarkable reductions in the number of diesel-driven trucks used, stemming from the introduction of collaborative measures.

As presented in **Fig. 4**, in Scenario 1, a mileage reduction of 51.9 % can be achieved in a monopolistic last-mile delivery system by establishing a white-label parcel service provider. Through the white-label logistics optimization, parcels are delivered to customers from any distribution center closest to them instead of a specific distribution center owned by a specific parcel service provider. In Scenario 2, 68.9% kilometres are saved by delivering to parcel stations compared to home delivery in the reference scenario. In Scenario 3, a 23% increase in mileage is recorded due to collaborative use of micro-depots while in Scenario 4, a 27.8% reduction in mileage is achieved through white-label PSP and white-label micro-depots. It is noteworthy that the mileage increase, recorded in Scenario 3 is primarily attributed to the lowest collaborative measure applied at the micro-depots. Since the PSPs retain their infrastructure and fleet but only share the micro-depot facilities, the potential gains are less evident, compared to other scenarios, where higher collaborative measures are applied. In general, the analysis of mileage performance demonstrates high potential savings through the implementation of collaborative use of dedicated space for logistics purposes. This effect is particularly pronounced for white-label and parcel station implementations.

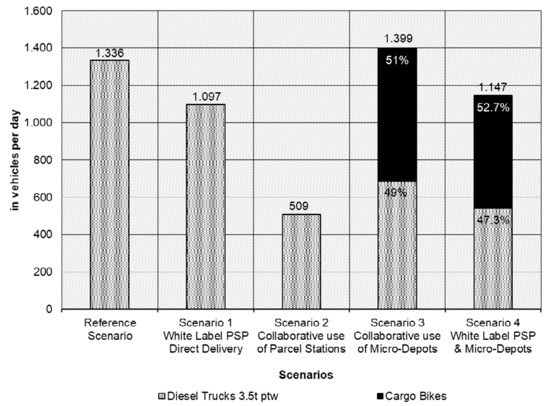

Fig. 3. Comparison of results for all scenarios: Total number of vehicles used per day

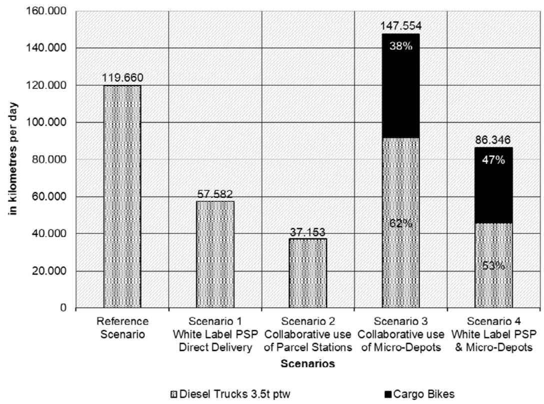

Fig. 4. Comparison of results for all scenarios: Total mileage performed per day

Fig. 5 compares the simulation results of the scenarios for the transport distance per tour. In comparison to the reference scenario, the transport distance per tour is almost 51% lower in Scenario 1. Scenario 2 produces a remarkable 68.3% reduction in the transport distance per tour. Furthermore, the average transport distance reduces by almost 22% in Scenario 3. Accordingly, the transport length per tour reduces by 61% in Scenario 4. The tour distance covered by the cargo bikes are on average about 10.3km in Scenario 3 and 10.8km in Scenario 4. The implementation of collaborative use of dedicated space in Scenario 1, 2, 3 and 4 record significant reductions in transport distance per tour. In particular, white-label logistics optimization, coupled with delivery to parcel stations in Scenario 2, results in the highest reduction in transport distance per tour. However, it should be pointed out that delivery to parcel stations and two-step distribution via micro-depots translates to a substantial decrease in the number of stops per tour for the trucks. In this approach, truck drivers can deliver several parcels at one location (at parcel stations and micro-depots), as opposed to making numerous short trips.

Fig. 6 shows the comparison of the simulation results of all scenarios regarding the transport time per tour. The transport time per tour comprises both the driving and stop time. In contrast to the reference scenario, the transport time for an average tour by means of trucks 3.5t ptw is 16.3% shorter in Scenario 1. In Scenario 2, the transport time for trucks is 61% less than in the reference scenario. In Scenario 3, a 47.7% reduction in the trucks' transport time per tour is achieved while in Scenario 4, a reduction in transport time per tour for trucks is 58.5%. The reduction in transport time per tour leads to savings in personnel cost per tour. On the one hand, these savings are particularly meaningful in Scenario 1 and 2 where a fewer tours are performed compared to the reference scenario. On the other hand, in Scenario 3 and 4, where a two-step distribution is implemented, additional tours are required for the cargo bike deliveries and as such, the savings in transport time per tour does not directly translate to substantial cost savings when the total personnel cost is considered.

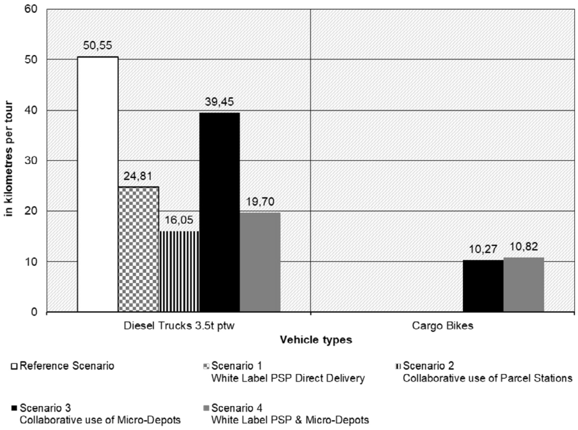

Fig. 5. Comparison of results for all scenarios: Transport distance per tour

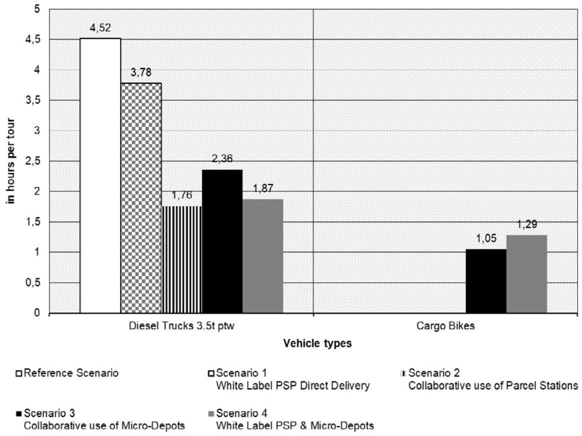

Fig. 6. Comparison of results for all scenarios: Transport time per tour

Impacts on transport costs

Fig. 7 shows that the total transport costs is 23.2% lesser in Scenario 1 compared to the reference scenario. In Scenario 2, total transport costs reduce by almost 63% compared to the reference scenario. In Scenario 3, the total transport costs increased by 12.4% and in Scenario 4, a 32.4% of the total transport costs is saved compared to the reference scenario. In general, collaborative distribution solutions lead to significant cost savings per day. As shown in **Fig. 7**, a substantial portion (59% - 76%) of the total transport costs per day arises from personnel costs. While promising outcomes are achieved from white-label and collaborative parcel station concepts, the results reveal that two-step distribution generates higher personnel costs, leading to a considerable increase in total transport cost.

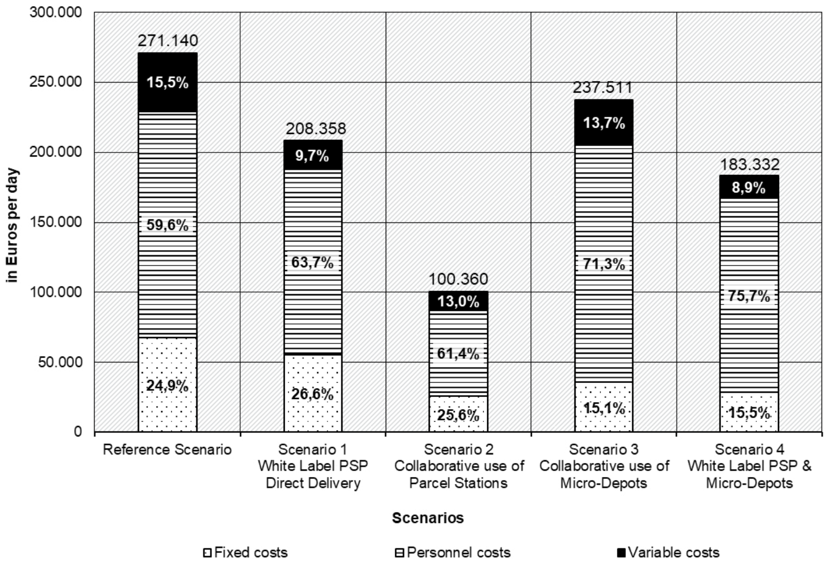

Fig. 7. Comparison of results for all scenarios: Transport costs per day

Impact on CO_2 emissions

Fig. 8 illustrates the impact of parcel delivery on carbon dioxide (CO_2) emissions, for all modelled scenarios. The CO_2 emissions generated result directly from the mileage performed. In the reference scenario, the exclusive delivery to private and commercial customers in the City of Hamburg by means of light commercial vehicles causes CO_2 emissions of over 27,900 kg CO_2-eq./day. Scenario 1 demonstrates that the emissions can be reduced by 52%. In Scenario 2, a decrease of 69% in CO_2 emissions can be expected while an emissions savings potential of 4% is recorded for Scenario 3 and of 48% for Scenario 4.

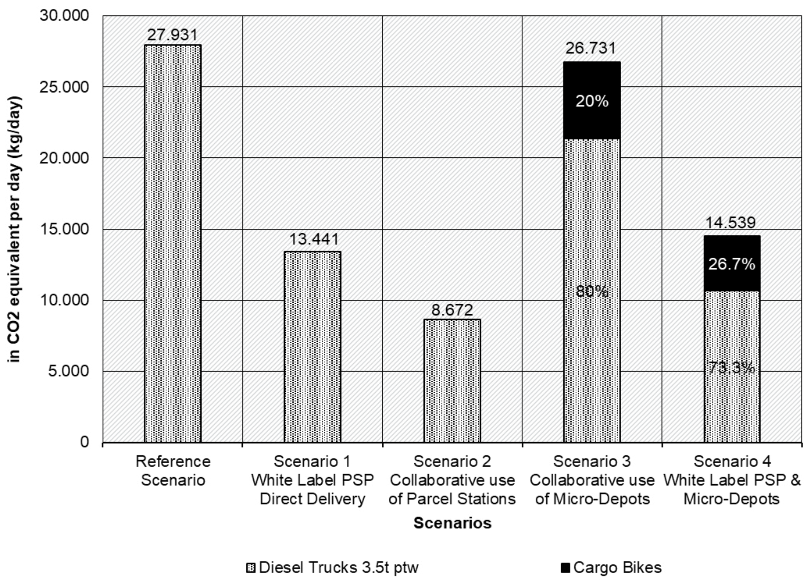

Fig. 8. Comparison of results for all scenarios: CO_2 emissions per day

Percentage deviation of transport-related, business and ecological key figures of collaborative scenarios from the reference scenario

Fig. 9 provides an overview of the relevant transport-related, business and ecological key figures for an average working day. The percentage deviation of the scenarios from the reference scenario is shown for each key figure. Costs or investments for micro-depots and parcel stations are not considered. It can be seen that in Scenario 1 and Scenario 2 the number of vehicles used decrease by 18% and 62% respectively. In Scenario 3 number of vehicles increase by over 4% while in Scenario 4, there are almost 15% less vehicles. The mileage is reduced by almost 52% in Scenario 1, a reduction of almost 69% in Scenario 2, 23.3% more mileage recorded in Scenario 3 while 27.8% less kilometres are performed in Scenario 4. The transport time reduces by almost 18% in Scenario 1 and by 61.9% in Scenario 2 but increases by almost 4.8% in Scenario 3 and reduces by 14.2% in Scenario 4. With regard to the business effects, a considerable reduction of 23.2% in transport costs can be observed in Scenario 1, almost 63% in Scenario 2, 12.4% in Scenario 3 and a saving potential of almost 32.4% in Scenario 4. Focusing on the ecological key value, it can be shown that CO_2 emissions can be reduced by 51.9% in Scenario 1 and up to 69% in Scenario 2, while a reduction of 4.3% is to be expected in Scenario 3 and a reduction of almost 48% in Scenario 4.

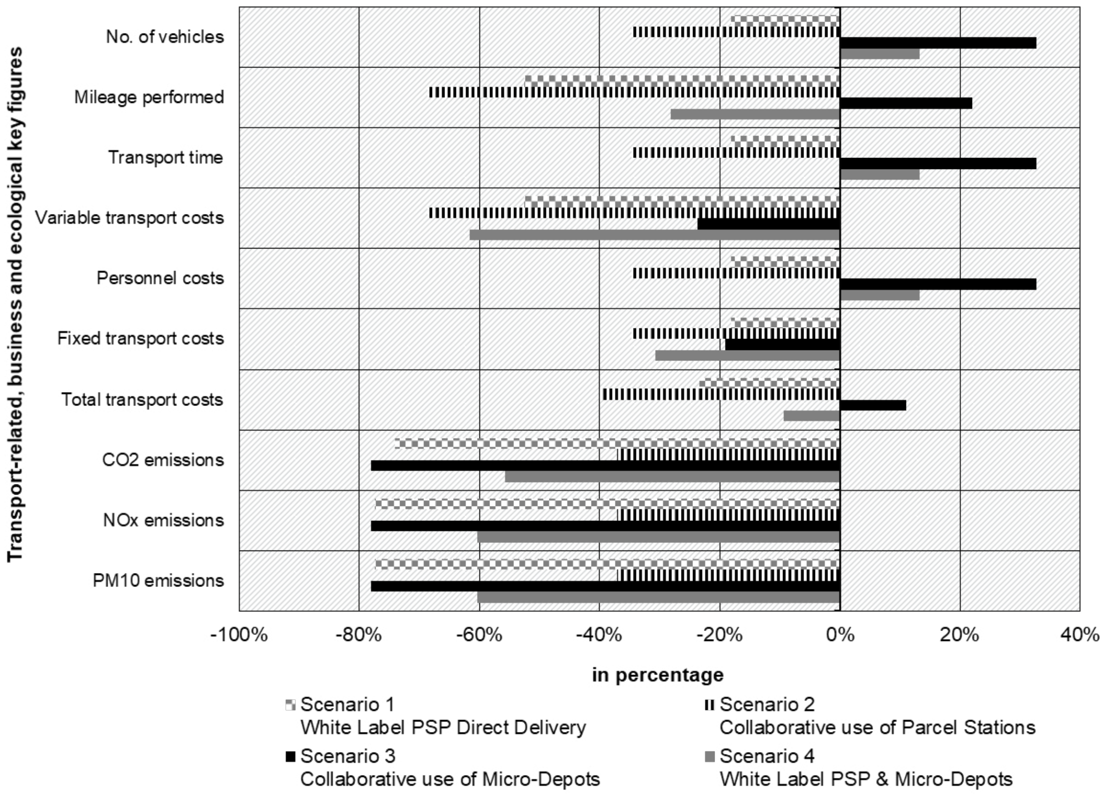

Fig. 9. Percentage deviation of the collaborative scenarios from the reference scenario

5. Discussion and recommendations for actions

The findings presented and discussed in this contribution have considerable transport planning and policy implications since they show that collaborative delivery solutions offer great potential in reducing the mileage performed, transport time and the resulting transport costs and emissions in the long term. According to the simulation results, the collaborative delivery of parcels in the City of Hamburg indicates significant reductions in certain key indicators investigated.

A white-label parcel service provider operating in the City of Hamburg which delivers parcels directly to private and commercial customers (Scenario 1) leads to significant reductions across all indicators examined. For the scenario modelled, where the white-label PSP delivers parcels of private customers to parcel stations (Scenario 2), a reduction in number of tours was achieved and remarkable lower mileage is performed compared to the reference scenarios.

Scenarios which consider the implementation of micro-depots (Scenario 3 and Scenario 4), record an increase in the number of tours. This is associated with additional cargo bikes required for the last mile delivery from micro-depots to the final customers and the capacity limitations of cargo bikes. The direct result of the introduction of micro-depots, is an increase in total mileage performed compared to the reference scenario. However, the two-step distribution process does not translate to a significant increase in the mileage performed when paired with a white-label PSP solution. A consistent outcome from the implementation of white-label solution is a reduction in the total mileage, leading to reductions in transport time and consequently transport costs savings. As a conclusion, establishing a white-label parcel delivery operator in the City of Hamburg would support the city authority in pursuing its goal to gain a reduction of emissions by 55% by 2030 compared to the 1990 baseline year (Hamburg Senate, 2019).

Additionally, it was observed that while collaborative use of micro-depots could potentially reduce the number of vehicles used and mileage performed, parcel stations can achieve significantly higher reduction in mileage performed. However, it needs to be considered that the share of delivery form for private customers has been modelled with 100% use of parcel stations in Scenario 2, with parcels rerouted to the nearest parcel branch if the nearest parcel station to the customer is full. Thus, it needs to be further investigated, whether a mixed share of delivery forms for private customers (e.g. use of parcel stations, home delivery, parcel shops and post offices) would lead to similar reductions in all indicators investigated. In this article, only two different delivery forms have been investigated: either 100% home delivery or 100% use of parcel stations. The mixed share of delivery forms also considering further forms like post branches and parcel shops has not been applied in this study and results in a future research opportunity. Another important aspect to consider is that in the scenarios when the parcel stations are used, the emissions of the people who will pick up their orders by car are not accounted in this study.

Furthermore, the highest potential for positive impacts is recorded in the scenario, in which a white-label parcel service provider is operating to deliver parcels to parcel stations for pick up by customers. The simulation results also demonstrate that high cost and emission savings could be achieved with the implementation of collaborative use of logistics facilities. In practice, the use of cargo bikes depends on the network design. Although their use leads to emission reductions, in particular their acceptance depends on the local quality level of the infrastructure and the willingness of the personnel to drive with cargo bikes. Moreover, the establishment of a white-label parcel service provider needs political guidance so that parcel service providers perceive the pressure to collaborate with competitors and inter-organizational consolidation can take place.

However, it needs to be mentioned that the micro-depots have been modelled with unlimited capacity and space and thus, further adjustment in the modelling and investigation needs to be done in future. Moreover, the investigation of an electric parcel delivery has been identified as a future research opportunity, since the City of Hamburg has announced to deliver cleaner urban transport through a mobility strategy as part of its Climate Action Plan, which includes the use of electric-driven vans and light duty vehicles for last mile delivery (Hamburg Senate, 2019). Parcel service providers aim to deliver emission-free to inner-city areas in the largest German cities by 2025 (Hermes, 2022). Therefore, spaces for logistics purposes for transshipment and consolidation need to be designated so that micro-depots can be implemented in inner-city areas that allow the use of cargo bikes on the final last mile. For this reason, a study has been conducted for the City of Hamburg that investigates which infrastructure is needed in future so that 25% of all parcels to private customers in the City of Hamburg can be performed with the use of electric-driven cargo bikes (Hamburg News, 2022). The results of the study suggest a size of 12 m^2 for a single-used micro-depot and a size of 30 to 50 m^2 for a collaboratively used micro-depot in urban areas (cargobike.jetzt GmbH, 2021).

Based on the findings of the simulation-based study, the highest savings in transport-related key figures as well as transport costs and emissions are recorded in Scenario 2. For this reason, the authors recommend a collaborative use of parcel stations in combination with a white-label PSP which delivers the parcels to it. In comparison to this, the collaborative use of micro-depots leads to an increase of vehicles – especially cargo bikes – needed for the very last mile. This results in the need for more staff who must also be fit enough to ride bicycles. In particular, the personnel costs increase for the PSP. In this study, the costs for investments and maintenance for the micro-depots is not considered, but these costs are very relevant for the PSPs. Most of the living labs with micro-depots were abandoned after the public funding ended due to maintenance costs (Buerklen, Schuete & Rudolph, 2023). For this reason, the collaborative use of micro-depots in combination with cargo bikes on the very last mile will remain a niche application.

In conclusion, the microscopic agent-based transport simulation MATSim and the linked route optimization Jsprit are suitable to investigate and to assess collaborative last mile delivery solutions regarding several aspects. Once the data collection and the compilation of the scenario setting is finalized, a comparative assessment of several distribution solutions in city logistics that are at choice can be performed. This supports the decision-making process in the field of urban freight transport planning and urban logistics.

6. Conclusion

The main purpose of this article was to explore the extent to which collaborative delivery solutions contribute to a more sustainable urban freight transport in the City of Hamburg and what impacts can be observed on relevant key values (e.g. number of trips, mileage performed, transport costs, emissions). One of the challenges associated with scientific assessment of freight transport is the limited access to information regarding the distribution of freight in particular in inner-city areas. Parcel service providers who possess these data prefer to keep them private as they are considered critical to the competitive advantage in business. Thus, demand estimation methods have been employed in this study to estimate the freight transport demand of parcel service providers to private and commercial customers. Input for the demand estimation include synthetic population dataset derived using accessible city population data and aggregated parcel demand from studies on the courier, express and parcel industry. The synthetic population for commercial clients has been derived from OpenStreetMap und classified according to the WZ 2008 for the own purpose. Furthermore, the Monte Carlo simulation technique has been applied for the disaggregation of the parcel demand and generation of a provider-customer distribution matrix. The logistics network structure of parcel service providers in Hamburg has been built up by means of an extensive Internet research to identify the locations of the providers (e.g. distribution centers, parcel shops, post office branches, parcel stations) and to georeference these locations for the synthetic simulation world. Agent-based simulation method has been deployed to simulate parcel distribution on the road infrastructure network of the City of Hamburg. Through this, aggregated and disaggregated results could be obtained from the urban freight transport model used to investigate collaborative and white-label delivery concepts for the parcel market in Hamburg.

To investigate the impacts of collaborative last mile solutions, four innovative delivery concepts were developed in this study. These concepts consider the implementation of modern urban logistics measures such as the implementation of parcel stations, micro-depots and the use of cargo bikes. Furthermore, this study provides an assessment of a white-label parcel service provider operating in the City of Hamburg. Thus, the following four scenarios were subsequently established:

- Scenario 1: White-label parcel service provider – Direct delivery
- Scenario 2: White-label parcel service provider – Collaborative use of parcel stations
- Scenario 3: Collaborative use of micro-depots – Collaborative share of dedicated space for logistics purposes
- Scenario 4: White-label parcel service provider – Collaborative use of micro-depots and vehicles used

The findings presented and discussed in this work have considerable freight transport planning and policy implications since they show that collaborative delivery solutions offer great potential in reducing the mileage performed, transport time and the resulting transport costs and emissions in the long term. According to the simulation results, the highest potential for positive impacts is recorded in the scenario, in which a white-label parcel service provider is operating to deliver parcels to parcel stations for pick up by customers. The simulation results also demonstrate that more cost savings and higher emission reduction could be achieved with the implementation of collaborative use of logistics facilities. As a conclusion, consolidation in distribution centers outside of city and a white-label parcel service provider operating in the City of Hamburg leads to significant reductions across all indicators investigated. Thus, establishing a white-label parcel service provider in the City of Hamburg would support the city authority in pursuing its goal to reduce CO_2-emissions by 55% by 2030 compared to the 1990 baseline year (Hamburg Senate, 2019).

Future research opportunity encompasses the investigation of a mixed share of delivery forms. Furthermore, modelling micro-depots with limited capacity and space would lead to more realistic results. Moreover, the investigation of an electric parcel delivery has been additionally identified as a future research opportunity, since the City of Hamburg has announced to deliver cleaner urban transport through a mobility strategy as part of its Climate Action Plan, which includes the use of electric-driven vans and light commercial vehicles for last mile delivery (Hamburg Senate, 2019). Parcel service providers therefore aim to deliver emission-free to inner-city areas in the largest German cities by 2025 (Buerklen, Schuete & Rudolph, 2023; Hermes, 2022). Thus, spaces for logistics purposes for transshipment and consolidation need to be designated so that micro-depots can be implemented in inner-city areas that allow the use of cargo bikes on the last mile (Buerklen, Schuete & Rudolph, 2023).

In conclusion, we recommend the establishment of a white-label parcel service provider who delivers mainly B2C parcels to parcel stations and parcel shops. We assess that the collaborative use of micro-depots along a two-step distribution in combination with the deployment of cargo bikes for the very last mile will remain a niche application. When electric-driven light commercial vehicles have fully penetrated the market, they will be more cost efficient than the cargo bikes and therefore will replace cargo bikes again.

In conclusion, a microscopic agent-based transport simulation MATSim and the linked route optimization Jsprit are suitable to investigate and to assess collaborative last mile delivery solutions regarding several aspects and enables a comparative assessment of a variety of distribution solutions in city logistics. Besides the assessment of logistics concepts, this modelling approach enables also the investigation of the effects of different vehicle technologies, logistics concepts and transport policy measures.

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Appendix A. Input data for Scenario 1 and 2

Scenarios	**Scenario 1**	**Scenario 2**	
Input parameter	**Value**	**Value**	**Unit***
Number of parcel stations	-	90	PS
Capacity per parcel station	-	111	PU/PS
Parcel demand			
Parcel demand B2C	118,367	118,367	PU/Day
Parcel demand B2B	229,509	229,509	PU/Day
Time windows of the commercial customers			
	06:00 ≤ 08:00 am	06:00 ≤ 08:00 am	
	08:00 ≤10:00 am	08:00 ≤10:00 am	
	10:00 - 12:00 am	10:00 - 12:00 am	
Preferred time windows of private customers			
17%	08:00 ≤ 12:00 am	08:00 ≤ 12:00 am	
18%	12:00 am ≤ 02:00 pm	12:00 am ≤ 02:00 pm	
30%	02:00 ≤ 06:00 pm	02:00 ≤ 06:00 pm	
35%	06:00 - 10:00 pm	06:00 - 10:00 pm	
Share of delivery form for private customers			
Home delivery	100	0	%
Parcel stations	0	100	%
Parcel shops, post offices	0	0	%
Stop time			
Constant stop time	60	60	s/St
Variable stop time	60	60	s/PU
Truck 3.5t ptw (diesel powered)			
Vehicle capacity	160	160	PU/V
Fixed costs	50,543655140	50,543655140	€/Day
Variable costs	0,000351163	0,000351163	€/m
Time dependent costs	0,004200975	0,004200975	€/s
Diesel consumption	0,000112000	0,000112000	l/m
AdBlue consumption	0,000001501	0,000001501	l/m
Max. velocity	42	42	m/s

***Legend:** MD = Micro-depot, PU = Parcel unit, PS = Parcel station, V = Vehicle, m = meter, s = second, St=stop

Appendix B. Input data for Scenario 3 and Scenario 4

Input parameter	Value	Unit*
Number of micro-depots	843	MD
Parcel demand		
Parcel demand B2C	118,367	PU/Day
Parcel demand B2B	229,509	PU/Day
Time windows of the commercial customers		
	06:00 ≤ 08:00 am	
	08:00 ≤10:00 am	
	10:00 - 12:00 am	
Preferred time windows of private customers		
17%	08:00 ≤ 12:00 am	
18%	12:00 am ≤ 02:00 pm	
30%	02:00 ≤ 06:00 pm	
35%	06:00 - 10:00 pm	
Share of delivery form for private customers		
Home delivery	100	%
Parcel stations	0	%
Parcel shops, post offices	0	%
Stop time		
Constant stop time	60	s/St
Variable stop time	60	s/PU
Truck 3.5t ptw (diesel powered)		
Vehicle capacity	160	PU/V
Fixed costs	50,543655140	€/Day
Variable costs	0,000351163	€/m
Time dependent costs	0,004200975	€/s
Diesel consumption	0,000112000	l/m
AdBlue consumption	0,000001501	l/m
Max. velocity	42	m/s
Cargo bike (370 kg ptw)		
Vehicle capacity	35	PU/V
Fixed costs	3,26731	€/Day
Variable costs	0,000103	€/m
Time dependent costs	0,0042009750	€/s
Energy consumption	0,00025	kWh/m
Max. velocity	6,94444	m/s

***Legend:** MD = Micro-depot, PU = Parcel unit, PS = Parcel station, V = Vehicle, m = meter, s = second, St=stop

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