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Analysis of logistics measures of CEP service providers for the last-mile delivery in small- and medium-sized cities: A case study for the Aachen city region

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Abstract

The e-commerce sector's rapid expansion has led to an increase in delivery activities both within and across cities, fuelling the growth of the courier, express, and parcel (CEP) services. CEP service providers are crucial for the distribution of goods across all types of cities, especially for last-mile delivery. However, CEP service providers need innovative approaches for their last-mile distribution in small- and medium-sized cities to reduce transport costs and negative environmental impacts. For this reason, this paper analyses the quantitative impacts of logistics measures of CEP service providers for last-mile delivery in small- and medium-sized cities, especially the resulting transport costs and environmental impacts, in the framework of a case study for the investigation area of the Aachen city region. A simulation-based analysis was conducted using the agent-based transport simulation MATSim and the linked route optimisation Jsprit. The results revealed that electric trucks are not cost-effective as a stand-alone logistics measure for last-mile delivery in small- and medium-sized cities. However, combining electric trucks with other sustainable logistics measures, such as parcel shops and parcel lockers, results in a viable logistics measure for last-mile delivery. It is possible to reduce total transport costs by at least 5.4% and CO_2 emissions by at least 61.1%. Hence, CEP service providers should replace diesel trucks with a mix of sustainable logistics measures for last-mile delivery in small- and medium-sized cities to achieve better operational efficiency and lesser environmental impacts.

Keywords Courier, Express and parcel (CEP) services, Electric trucks, Logistics measures, Cargo bikes, Parcel lockers, Microscopic, Agent-based transport modelling, MATSim, Vehicle routing problem, Jsprit, Impact assessment

1 Introduction

Over the last decades, the total volume of freight transport that goes into and out of cities has grown simultaneously with urban population expansion and e-commerce growth. As a submarket of the freight transport or transport logistics industry, the courier, express, and parcel (CEP) service market has experienced a similar growth pattern. The g of the CEP services has been propelled by e-commerce growth coupled with increasing demand for fast delivery by customers. Furthermore, the COVID-19 pandemic rapidly influenced the global parcel volume between 2019 and 2022, causing it to reach 131.2 billion parcels in 2020 (a 27% increase from 2019) and 159 billion parcels in 2021 (a 21.2% increase from 2020). In 2022, the rapid growth rate of global parcel volume declined due to inflation and the ending of the COVID-19 pandemic.

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As a result, the global parcel volume was 161 billion parcels in 2022, but it is projected to gradually recover and grow at a 6% cumulative annual growth rate from 2023 to 2028, leading to 225 billion parcels in 2028 [47]. Thus, the number of deliveries managed by CEP service providers within and across cities keeps increasing.

CEP service providers have explored several logistics measures over time to address the growing demand for quick delivery services to improve delivery performance and reduce transport costs, particularly on the last-mile. The last-mile is considered the costliest segment of the logistics chain due to several factors. According to [10], the share of costs on the last-mile can range from 50% to 60% of the total supply chain costs depending on the consignment structure, recipient structure, depot structure and organisation of the transport processes. This is because the last-mile has the least degree of automation in parcel logistics and requires a large amount of personnel for loading and delivery. Consequently, CEP service providers are shifting to sustainable logistics measures for last-mile delivery, but this is only prominent in largely populated cities such as Munich, Berlin, Paris, etc.

CEP service providers need innovative approaches for their last-mile distribution in small- and medium-sized cities to reduce transport costs and negative environmental impacts. The use of diesel trucks for last-mile delivery in these kinds of cities is often considered the most viable logistics measure, which may be counterproductive and, thus, warrants a study of last-mile delivery in the context of small- and medium-sized cities. Such cities are considered because of their spatial structure, characterised by middle to low population density and sparsely distributed delivery destinations. These highlighted challenges motivate the simulation-based analysis of logistics measures of CEP service providers for last-mile delivery in small- and medium-sized cities, especially the resulting transport costs and environmental impacts.

The goal of this paper is to analyse the effects of implementing logistics measures in small- and medium-sized cities, especially the transport-related and environmental impacts. To the best of our knowledge, very little attention is given to such analysis in small- and medium-sized cities. Thus, the contributions of this paper are as follows:

- Identification of feasible logistics measures of CEP service providers for last-mile delivery in small- and medium-sized cities.
- Overview of potential combinations of sustainable logistics measures for last-mile delivery by CEP service providers.
- Investigating and assessing the resulting effects of implementing the potential mix of sustainable logistics measures for last-mile delivery in freight transport and the resulting transport costs and emissions.

The contributions will aid in reorienting CEP service providers regarding their choice of logistics measures for last-mile delivery in small- and medium-sized cities. Furthermore, this paper also supports the decision of CEP service providers to switch from using diesel trucks to other sustainable logistics measures with better operational and environmental effects. For this purpose, a simulation study for an ex-ante analysis is set up to evaluate selected logistics measures for last-mile delivery and their impacts on relevant parameters regarding efficiency (e.g. transport costs, number of stops, transport time, etc.) and environment (e.g. emissions). Therefore, the microscopic agent-based transport simulation MATSim [29] and the linked route optimisation Jsprit [51] are used for which a synthetic world for the Aachen city region has been built up focusing on the CEP market with respectively parcel service providers as well as their private and commercial customers.

The remainder of this paper is structured as follows: a review of the relevant state of the art in the fields of urban freight transport modelling, last-mile delivery and logistics measures of CEP service providers will be provided in section 2. Afterwards, the methodology used will be presented, i.e., the functionality of MATSim and Jsprit will be shown as they apply to this paper (Section 3). Then, the case study will be defined along with the scenarios to be evaluated (Section 4). Subsequently, the results will be presented and the insights will be discussed in detail (Sections 5 and 6). Finally, the conclusion and limitations as well as outlook will be stated in section 7.

2 Literature review

In the following section, the state of the art in urban freight transport modelling, last-mile delivery and the logistics measures of CEP service providers will be presented.

2.1 Urban freight transport modelling

Several models have been developed to understand and evaluate the activities involved in urban freight distribution. In general, three kinds of models have been developed over the years to model the freight transport system and urban freight distribution. The three kinds are traditional four-step models, trip-based models and goods-flow models. The first set of freight transport models, based on the traditional four-step approach, was unable to determine the transport-related impacts of the freight transport system per se. This is because the use of this approach often results in the representation of freight transport as an approximate percentage of other traffic [11].

Holguin-Veras and Thorson [28] proposed a first-order trip chain model to estimate and analyse the occurrence of empty vehicle trips in freight transport. They emphasised that neglecting empty trips can lead to inaccurate freight transport modelling, as empty trips contribute significantly to vehicle mileage travelled and emissions. Boerkamps and Van Binsbergen [11] developed the GoodTrip model (an urban, goods flow-based transport simulation model) to estimate the logistical performance and environmental effects of urban freight distribution. The GoodTrip model was based on the structure of the supply chains and was noted to be a good tool for evaluating large changes involving new infrastructures and small changes such as improved cooperation between transport companies or other vehicle routing strategies.

The Freturb model is also an important model that has been utilised to analyse and optimise freight transport and urban freight distribution within cities. It was first developed in the 1990s by the Laboratoire d'Économie des Transports (LET) in France, and the software tool has been upgraded since then. The Freturb model has proven to be effective in simulating complex urban freight distribution scenarios and helping to understand the impacts of urban policies while minimising negative environmental impacts [5, 49]. The work of Ambrosini et al. [5], which analysed how different urban policies influence the freight transport in urban areas using the Freturb model, highlighted the model's ability to estimate the impacts of changes such as activity relocation. Similarly, the work of [49], which studied three modules (a delivery-pick-up model, a town management module, and a purchasing trips model) interacting with each other, yielded the same conclusion on the effectiveness of the model.

Agent-based simulation has become a common technique to evaluate the freight transport system and urban freight distribution because it allows to model the behaviour of each agent in the system. Thus, there is a better understanding of the system and decentralisation of decision-making across the system. Liedtke [35] presented the underlying micro-behavioural modelling of commodity transport and used it to evaluate the effects and adaptive reactions of behaviour-oriented transport policy measures while taking complicated logistics patterns into account. The study demonstrated that the impacts of logistical rearrangement can be replicated by multi-actor multi-simulation. Furthermore, Roorda et al. [48] developed a comprehensive conceptual framework for agent-based modelling that is especially suited to logistics services, in order to enhance the comprehension and management of logistics operations through its emphasis on the actions and interactions of individual agents. The proposed framework offered a robust and adaptable tool with consideration for policy issues, business trends, and technological advancements.

Roorda et al. [34, 48] and Davidsson et al. [18] developed agent-based models in long-distance freight transport to enable the illustration of the heterogeneity and the different objectives of the decision-makers. de Bok and Tavasszy [12] developed and validated an agent-based model that illustrates urban freight transport patterns and the underlying logistics decision-making using a large dataset of observed freight transport in the Netherlands. Schröder et al. [51] developed the route optimisation Jsprit and linked it to the Multi-Agent Transport Simulation (MATSim) to analyse logistics stakeholders (shipper and carrier) and their behaviour at the urban level. Comi and Savchenko [15] proposed a methodology to help select the most environmentally friendly mode to fulfil the last-mile delivery of small parcels in urban cities, based on external and internal costs incurred from using each mode. The proposed methodology quantifies the external and internal costs to enhance the planning and execution of last-mile delivery in urban cities.

2.2 Courier, express and parcel (CEP) services

The CEP service market is one of the fastest-growing industries globally [9] and has been an important one in the freight transport sector across regions in the last decades, benefiting regions through employment creation and revenue generation. CEP services can be described as logistics and postal service providers specialising in moving parcels [10]. These parcels vary in size and weight, from small packages such as letters to heavy items weighing 30 kilograms, and are intended as a Business-to-Business (B2B), Business-to-Consumer (B2C) or Consumer-to-Consumer (C2C) delivery [57]. Private household and retail demand in urban agglomerations account for most of the volume of freight goods handled by CEP service providers [16]. In addition, CEP service providers, as the term implies, render courier, express and parcel services. These three types of services appear similar but differ in terms of weight, delivery time, speed, and type of accompaniment. Furthermore, road freight transport remains dominant for fulfilling CEP services, especially on the last-mile leg. However, the mode of transport utilised depends on the mileage to be performed, shipment size and customers' choice of service with respect to the desired delivery period and willingness to pay.

Freight operations of CEP service providers have various legs in the entire supply chain process. Therefore, CEP service providers' decision-making and freight-related activities vary depending on functional connections and the transport chain being executed. The last-mile delivery can be defined as the final leg in a business-to-business and/or business-to-consumer delivery service whereby the consignment is delivered to the recipient, either at the recipient's home or at a collection point [23]. The last-mile delivery is influenced by structural elements (e.g., transport system, location and size of distribution centres), supply chain locations, and commercial and market factors (like freight demand and transport demand, supply chain strategies, and company activities). It also depends on operational and functional elements like route and vehicle planning, as well as policy measures of the public authority [6]. As a result, the quality of service, transport cost and environmental impacts can be used to assess the efficiency of the last-mile delivery.

2.3 Logistics measures on the last-mile delivery

Several studies have been made in the field of last-mile delivery of freight goods in urban cities. CEP service providers aim to optimise freight delivery operations by ensuring swift delivery times, minimising mileage performed, vehicles utilised, transport time and the resulting transport costs, and increasing revenue [16]. Therefore, CEP service providers need to select the most suitable logistics measure for last-mile delivery in a region to achieve operational efficiency. Measures on last-mile delivery are short-term based and aimed at operational efficiency with emphasis on profitability, effective time management, mileage performed and operating transport costs [14, 16, 23]. In addition, customers' need for flexibility in terms of when, where, and how they get their parcels has created a trend towards urban localisation enabled by service stations, parcel lockers, cargo bike delivery, electric vehicles, etc., thus shortening the last-mile [20]. These measures may be technologically aided, and they reflect the CEP service provider's decisions on vehicle type utilised, home or not-at-home delivery, the possibility for collaboration with other competitors (if any), etc. The logistics measures implemented or proposed for last-mile delivery of CEP services are identified based on their delivery types [23]. There are mainly two delivery types, and they are direct delivery and indirect delivery, as shown in Figs. 1 and 2.

Direct delivery - On the last-mile leg, direct delivery refers to the transport of parcels from the distribution centre to the final customer without a transshipment process between them. Furthermore, the recipient does not cover any distance to receive the parcel. This type of delivery saves time, makes it easy to track the parcel and can reduce operating costs related to warehousing and transshipment.

Indirect delivery - On the last-mile leg, indirect delivery involves an intermediate facility between the CEP service provider's distribution centre and the final recipient of the parcel. The CEP service providers may also fulfill the delivery via their parcel locker, postal office, or registered parcel shop. In such cases, deliveries would require the final recipient to cover some distance to collect the parcel. Nevertheless, indirect delivery allows CEP service providers to expand their catchment area and tackle high seasonal demand.

2.3.1 Conventional trucks

Conventional trucks with internal combustion engines have been the traditional means of transport for last-mile delivery in the CEP sector over the last decades. Although some conventional trucks use gasoline, diesel remains the most utilised power source for commercial conventional trucks because of its benefits over gasoline. However, studies have shown that both diesel- and gasoline-powered delivery vehicles (trucks and vans) emit alarming levels of CO_2 into the atmosphere [7, 39]. Light diesel trucks with a permissible weight of 3 to 4

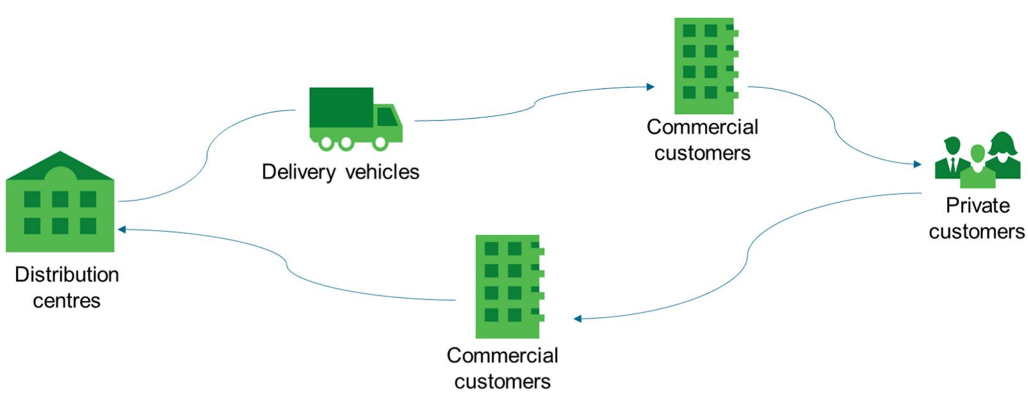

Fig. 1 Direct delivery

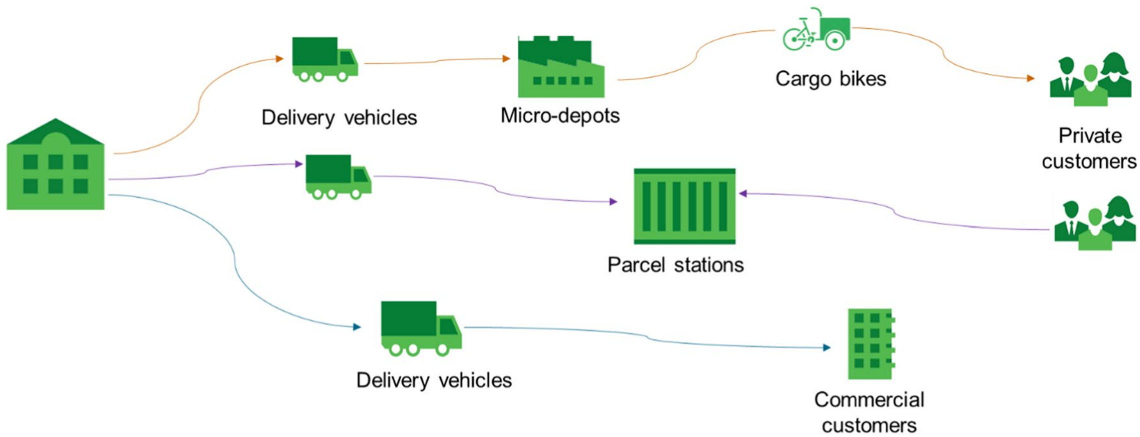

Fig. 2 Indirect delivery

tonnes are the common vehicle size utilised by CEP service providers for last-mile deliveries due to weight limitations and other road policies of public authority. Even though CEP service providers still have light-diesel vans and trucks in their fleets, the campaign to replace them with other sustainable truck or vehicle types for last-mile delivery is being advocated.

2.3.2 Electric-driven trucks

Electric-driven vehicles have been advocated, in recent years, as a viable alternative to conventional trucks for freight transport. Electric-driven trucks are environmentally friendly trucks that use electricity instead of diesel or gasoline to power their engine. However, they are more expensive to acquire, making conventional trucks still more preferred by small- and medium-sized logistics firms for CEP services. Thus, CEP service providers often require some impetus (such as promoting their brand, government grant or tax relief) to adopt electric-driven trucks/vans into their fleets [33, 39]. The adoption of electric-driven vans/trucks for freight transport has been slow due to battery limitation, distance-based emission factors and inadequate public charging infrastructure [7, 32, 39, 43]. Battery electric vans are the most preferred for last-mile delivery within urban areas due to their reliability and usefulness [31, 33].

Various fuel types have been researched and implemented to generate the electricity required to power electric-driven vehicles, giving rise to the variety of electric-driven vehicles in the market today. The various types of electric-driven vehicles based on the power source and configuration are battery electric vehicles (BEV), fuel cell electric vehicles (FCEV) and hybrid electric vehicles (HEV). Hybrid electric vehicles have more than one type of power source, usually an internal combustion engine and an electric motor. The different types of electric vehicles have certain advantages over one another within certain circumstances. Their overall performance depends on vehicle type, vehicle technology, infrastructure, operating conditions, and related costs [31]. In general, the benefits of electric-driven vans/trucks are higher energy efficiency, low noise emissions, low CO_2 emissions, and cheaper operating costs. Adeniran et al. [4] argued that electric-driven trucks can decrease CO_2, NO_X and PM_{10} emissions produced during parcel delivery when compared to diesel trucks, but they are unable to decrease the mileage performed and total transport costs, especially when the trucks have the same total permissible weight.

In general, electric-driven trucks/vans are emission-free but the production plant where the electricity is generated is not emission-free. As a result, the use of well-to-wheel analysis to assess the overall emissions of electric-driven vehicles is important, i.e., emissions from driving the vehicle and emissions from the production plants generating the electricity that powers the electric-driven van/truck [25]. Renewable energy sources are recommended to maximise the emission-free benefit of electric-driven vehicles [25, 32]. CEP service providers have increasingly integrated electric-driven vans/trucks into their fleets. According to the DHL 2019 sustainability report [19], DHL performed 15% of all post and parcel deliveries in Germany in 2019 using electric-driven vans and trucks, given their zero-emission delivery goal. A study on UPS stated that using electric-driven trucks (mostly battery electric trucks) in 2016 saved 20,015 litres of diesel and 52.84 tonnes of carbon dioxide [55].

2.3.3 Cargo bikes

Cargo bikes are two-/three-wheelers with a big compartment that is suitable for last-mile delivery and collection activities [42]. Cargo bikes are environmentally friendly and can be utilised to make short tours from the local distribution centre. They are appropriate for locations with narrow streets, high business activity and delivery density [41, 52, 55]. Electric cargo bikes (known as e-cargo bikes) are cargo bikes with electric assistance to the rider for ease of use. In addition, cargo bikes are cheaper than conventional and electric-driven vans/trucks, but they do not have a direct replacement ratio, i.e., a cargo bike does not completely replace a diesel/electric-driven truck due to notable differences like payload and speed.

Several studies have assessed the operational viability of cargo bikes for last-mile delivery against vans and trucks in terms of transport costs, transport time and emissions. [24] highlighted that spatial context (trip distance, elevation levels of origin and destination, availability of good cycling infrastructure), time (peak or off-peak period), cargo cycle type (number of wheels, the presence and type of electric assist) and trip conditions (weather condition) are the factors that influence the transport time differences of cargo bikes when compared to automobiles. Thus, the transport time difference between cargo bikes and trucks can vary because it depends on the overall context of the freight trip. According to [40], using Porto (Portugal) as the study area, e-cargo bikes can potentially substitute up to 10% of conventional commercial vans and reduce CO_2 emissions significantly by up to 73% when used in a suitable spatial context. Zhang et al. [60] assessed the utilisation of cargo bikes for urban parcel delivery in Berlin-Wilmersdorf, Germany, and they concluded that cargo bikes could reduce transport costs and emissions by 28% and 22%, respectively.

Nocerino et al. [44] investigated the economic and environmental impacts of using e-bikes and e-scooters for urban logistics through pilot projects carried out in several Italian cities under the Pro-E-bike initiative. The projects were aimed at promoting modal shifts to less polluting modes and promoting collaboration and knowledge exchange among stakeholders. They highlighted that the adoption of e-bikes and e-scooters for urban logistics as alternatives to traditional vans has economic benefits (such as lower operating costs and a better return on investment), environmental benefits (such as reduction of CO_2 and energy consumption and improvement in urban air quality), and operational benefits (such as improvement in delivery efficiency). According to Dalla Chiara et al. [17], the availability of good infrastructure designed for cargo bikes is essential to promoting the use of cargo bikes for urban freight distribution.

Cargo bikes can equally improve the traffic conditions of the network within which they are operated due to less interference with road traffic [36, 41, 55]. Cargo bikes are increasingly being utilised (especially e-cargo bikes) because they are more energy efficient, cheaper to operate, emit fewer emissions, and create more jobs. However, two major limitations of cargo bikes are limited payload and range compared to conventional and electric-driven trucks/vans. As a result, they require support to expand their operational area from the immediate surroundings of the local distribution centres. Micro-depots are proposed as a viable solution to increase the operational effectiveness of cargo bikes for last-mile delivery. Micro-depots are strategically positioned logistics hubs across the network from which cargo bikes can start their delivery trips.

Hofmann et al. [27] conducted a simulation-based evaluation for multimodal distribution plans using Grenoble, France. They identified possible transhipment points for micro-depots to integrate cargo bikes into urban distribution as well as the potential benefits of cargo bikes in reducing total mileage performed, traffic congestion and CO_2 emissions and improving air quality. According to [55], United Parcel Service (UPS) participated in the City2Share project in 2016 which involved using micro-depots and cargo bikes for parcel delivery in urban areas. The project enabled UPS to reduce the mileage performed, save about 30,000 litres of diesel within a year and decrease the resulting CO_2 emissions by about 120 tonnes. They argued that cargo bikes with micro-depots are suitable for densely inhabited regions and that the integration of multiple delivery concepts might be necessary for some cities for efficiency.

Marujo et al. [38] proposed a mobile depot concept, in which a truck serves as a mobile depot while cargo bikes pick up parcels from the truck to deliver to recipients, to optimise urban freight distribution in dense cities. Using Rio de Janeiro, they evaluated the economic, environmental, and operational impacts of their concept, and it was observed that cargo bikes alongside mobile depots for urban freight distribution can lead to a significant reduction in emissions, lower costs, and improved air quality. Caggiani et al. [13] developed a robust decision support system (DSS) that takes into account the effectiveness of logistics performance and the ability of e-cargo bike drivers to select the optimal route for last-mile delivery using e-cargo bikes, by weighing two criteria, which are the minimum travel time and the minimum amount of emissions.

[36] also studied cargo bikes for parcel deliveries by means of the FOCA (Freight Orchestrator for Commodity flow Allocation) model. In the framework of a case study for Munich, Germany, they observed that using a high number of cargo bikes alongside micro-depots reduces the total mileage performed. However, very low-demand locations (such as those with less than 100 parcels per km^2) require much more work and might

be less viable for cargo bikes. In addition, they noted that changes in micro-depot density affect the number of tours of cargo bikes and total mileage performed. The outcome of using a micro-depot also depends on the storage capacity of the micro-depot, the availability of cargo bikes and a good scheduling strategy [22, 24, 27, 50]. The application of micro-depots is still new and being explored. Hence, studies on micro-depot prospects are often based on potential locations such as post offices [60] and idle urban space - parking spaces in front of shopping centres and supermarkets [22].

2.3.4 Parcel shops and parcel lockers

Parcel shops are retail stores that offer parcel collection and dispatch services to private customers on behalf of a CEP service provider. All major CEP service providers are exploring the parcel shop concept to expand their catchment area. Parcel lockers are secure automated booths that offer self-services to customers concerning the collection and dispatch of parcels [56]. Parcel lockers are ideal for large parcels that cannot fit household mailboxes and postal services outside regular working hours. Examples of parcel lockers are DHL parcel stations in Germany and Amazon hub lockers. Private customers are usually required to cover a walkable distance to parcel shops or lockers to access their services. However, they offer private customers a longer time window to pick up their parcels in contrast to home delivery. Therefore, they save time and can reduce failed home deliveries and transport costs.

According to Sułkowski et al. [56], the use of parcel lockers is a viable last-mile delivery solution for now and in the future. Although, there is a need to increase the parcel locker's capacity and information technology integration. Furthermore, [57] also examined the use of parcel stations for CEP deliveries in the framework of a case study for Berlin, Germany. The results revealed that the use of parcel stations can reduce mileage performed, fuel consumption, fleet stock required, transport costs and emissions. Zhang et al. [60] also stated that the use of parcel stations can reduce the mileage performed because fewer stops are made, which leads to reduction of the transport time by about 16.8%.

2.4 Deriving the research gap

Studies have proposed several sustainable logistics measures for last-mile delivery and some have been implemented by CEP service providers. However, the applications of these sustainable logistics measures are often tested/implemented on a large scale such as on a country basis (Germany, Italy, Poland, the Netherlands, the United Kingdom, etc.) or in large-sized cities. Examples of such large-sized cities' applications are Berlin, Germany [3, 50, 57, 60], Munich, Germany [36, 55], Hamburg, Germany [55], Vienna, Austria [22], Toronto, Canada [48], Rio de Janeiro, Brasil [38], and Seattle, the United States [17]. Though Hofmann et al. [27] used a medium-sized city known as Grenoble in France in their study on the integration of cargo bikes into an urban distribution system. There are hardly any applications of sustainable logistics measures for last-mile delivery in small- and medium-sized cities. Hence, this paper analyses sustainable logistics measures of CEP service providers for last-mile delivery in small- and medium-sized cities, with emphasis on the resulting transport costs and environmental impacts. The logistics measures of CEP service providers for last-mile delivery, identified from the literature review, are conventional trucks, electric-driven trucks, cargo bikes with micro-depots, parcel shops and parcel lockers.

3 Methodology

In the following section, the methodological approach will be described in-depth. Following the literature review on logistics measures of CEP service providers for last-mile delivery, a simulation-based framework is adopted to assess the suitability of the identified logistics measures for last-mile delivery in small- and medium-sized cities. The simulation-based framework is based on the agent-based transport simulation MATSim [29] and the linked route optimisation Jsprit [51]. This approach is used because it allows for the behavioural modelling of concerned actors within the logistics system. MATSim is an agent-based modelling software that helps to evaluate transport-related problems at a mesoscopic level and supports decision-making on potential solutions. Using MATSim, each agent within the system interacts with its environment and tries to maximise its utility but not to the detriment of another. Jsprit offers computational strategies for resolving the travelling salesman problem (TSP) and vehicle routing problems (VRPs) [51]. The functionalities of Jsprit include choosing a daily plan, setting the vehicle type, assigning the distribution centre from which a customer is supplied, defining the order of customers to be served per route, and setting the departure time from the distribution centres. The methodological procedure is shown in Fig. 3.

3.1 Modelling framework

Jsprit can be linked to MATSim using a freight plugin to simulate the logistics choices made by logistics service providers. The activities of CEP service providers and their resulting impacts have been studied using a combination of MATSim and Jsprit. For example, Schröder

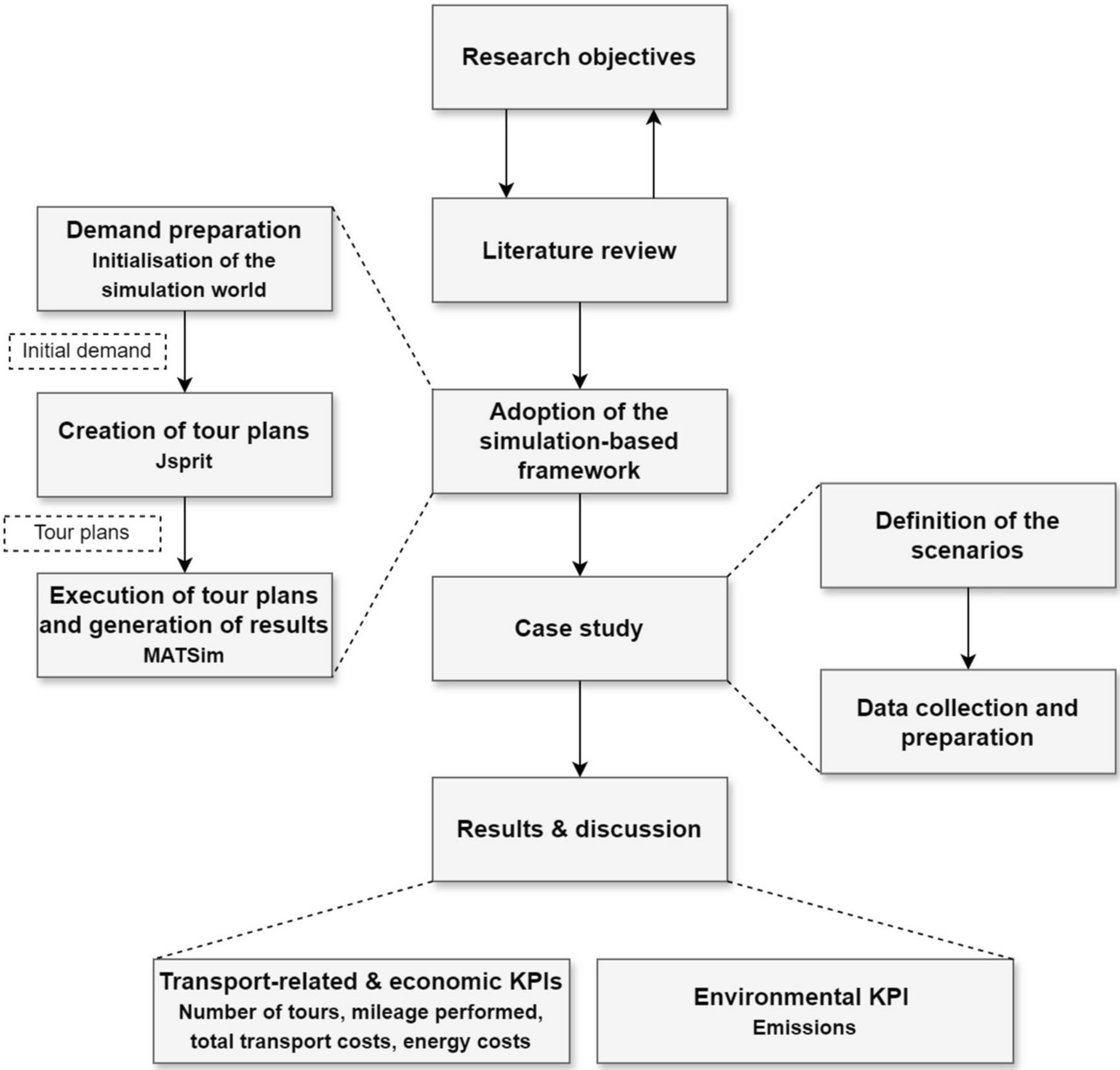

Fig. 3 Methodological framework (Own diagram)

et al. [52] analysed smart policy options for urban food distribution using MATSim and Jsprit. [57] combined them with a system dynamics model to assess various policy initiatives and logistics measures for CEP delivery in urban areas and the future development of CEP transport. Zhang et al. [60] assessed the utilisation of cargo bikes and parcel pickup points in urban parcel delivery using MATSim with Jsprit. [3] also used MATSim and Jsprit to analyse the impacts of certain sustainable measures in CEP delivery systems. These studies are the basis and guide for applying MATSim with Jsprit in this paper. The combination of MATSim and Jsprit allows for an extensive analysis of the transport-related effects of parcel transport on a disaggregated infrastructural level.

The objective function, in the Jsprit algorithm, of every freight agent in the system is as follows:

$$\mathbf{min}\{C_{fixed} + C_{act} + C_{waiting} + C_{late} + C_{transport}\}$$

C_{fixed} = *Fixed costs of the vehicle* C_{act} = *Costs for delivering to the customer* C_{waiting} = *Costs for early arrival at the customer* C_{late} = *Costs for late arrival at the customer* $C_{\mathrm{transport}}$ = *Transport costs of all vehicles used* The following constraints are applied while using Jsprit to optimise transport costs:

- The delivery trips to the (commercial and private) customers start at the respective distribution centre.
- The delivery quantities to the customers are known in advance.

- The delivery times of the deliveries can be limited by time windows.
- Each carrier is assigned a vehicle fleet consisting of different vehicle types. The vehicle types differ in terms of capacity and costs.
- All vehicles start and end at the distribution centre.
- A maximum of one route per day can be assigned to a vehicle.

3.2 Description of the modelled system

The modelling procedure of the combined application of MATSim and Jsprit has three stages. Demand preparation is the first stage, where input data are loaded to initialise the simulation world. To set up the modelled system, input files for the case study must be collected. The main input files required for modelling the freight system are network file, vehicle type and specifications, fleet size, transhipment locations, private customers, commercial customers and CEP service providers, i.e., their distribution centres, post offices, parcel shops and parcel lockers (see Table 1). All location information must be in one coordinate reference system appropriate for the study area (e.g., the GK Zone 4 coordinate system because it is one of the most appropriate coordinate reference systems for the geographical region of Germany). Detailed information on the preparation for input data and processing for initializing the synthetic world can be found in [57].

In the second stage, the simulation is initiated to run using the model which reads in the input files and parameter values. The model generates the tour plans based on customers' requests for the carrier agents using Jsprit. Each customer's (whether private or commercial) request is first sent to the CEP service provider and then assigned to the distribution centre closest to the customer. Afterwards, customers' requests are harmonised and merged at the distribution centres, which are then transferred to Jsprit. For Jsprit to compute tour plans, it requires the number of shipments, operating time windows, the number of vehicles and their characteristics, and the type of delivery to private and commercial customers. Each tour plan contains the start and end points of the tour, points of delivery, number of parcels ordered per stop, type of delivery for private customers, and delivery time windows for customers. The tour plans are then executed in the infrastructure network using MATSim.

Each carrier has a distribution centre, a set of vehicles, private and commercial customers and a tour schedule. In Jsprit, the carrier acts as the freight agent and decides the daily delivery plans to be carried out. Each carrier can choose the set of vehicles and vehicle types to be utilised, the distribution centre from which

Table 1 Input data for modelling

Inputs	Description	Data format
Infrastructure network	Links with length, number of lanes, capacity per lane, max. velocity	.xml file
	Georeferenced nodes	
Private customers	Georeferenced locations of private individuals based on census data of the population	.xlsx file
	Number of people differentiated in age cohorts per statistical block	
	Number of private customers of CEP service providers: using the actual share of private e-commerce users	
	Selection of private customers of CEP-service providers: randomly determining the potential e-commerce users	
Commercial customers	Georeferenced locations of the companies	.xlsx file
	Selecting CEP affine companies, e.g. retail, gastronomy, service, administration and research	
Distribution centres	Georeferenced locations of the distribution centres of the CEP service providers i.e., Deutsche Post DHL, GLS, DPD, Hermes and UPS	.xlsx file
Post offices	Georeferenced locations of post offices of Deutsche Post DHL, GLS, DPD, Hermes and UPS	.xlsx file
Parcel shops	Georeferenced locations of parcel shops of Deutsche Post DHL, GLS, DPD, Hermes and UPS	.xlsx file
Parcel lockers	Georeferenced locations of DHL parcel lockers and Amazon lockers	.xlsx file
Micro-depots	Georeferenced locations of parking areas in front of supermarkets and shopping centres	.xlsx file
Freight demand	Number of parcels for private clients for a typical day	.xlsx file
	Number of parcels for commercial clients for a typical day	
	Distribution of the parcels randomly to the potential e-commerce users	
	Distribution of the parcels to the commercial clients (sum of parcels/number of commercial clients)	
	Clients send an order to the CEP service provider	
Freight vehicles	Different types of vehicles used and their respective technical specifications (e.g. vehicle capacity, maximum velocity, fuel consumption per km, fixed transport costs per vehicle and day, variable transport costs per km, time-dependent transport costs per hour)	.xml file

the customer is supplied, the departure time from the distribution centres and the order in which the parcels are delivered to customers on the tour. The execution in MATSim establishes the network route between the customers.

In the third stage, the executed tour plans are assessed based on cost-benefit functions and, if required, they are rescheduled in a subsequent iteration until a system optimum is achieved. For a detailed explanation of the modelled system, kindly refer to [3], Adeniran et al. [4], Schröder et al. [52] and [57]. The following further own assumptions for our case study on the CEP market are made for the modelled system.

- The average speed per edge was used to account for the surrounding traffic and congestion on the road network because the road network was not calibrated.
- All CEP service providers have defined market share.
- A customer is randomly assigned to a CEP service provider at the start of the simulation using a Monte Carlo simulation technique.
- The parcels of customers are delivered from the nearest distribution centre of the CEP service provider assigned to them.
- All CEP service providers have their own vehicles and drivers.
- Average time required to deliver a parcel at a customer location is 2 minutes.

Fig. 4 Map of Aachen City Region

4 Case study: CEP transport in the Aachen city region

In this section, the case study focusing on CEP transport in the Aachen city region (Städteregion Aachen; shown in Fig. 4) will be presented. First, the reasons for choosing the logistics sector CEP market and the investigation area Aachen city region will be explained. Then, the scenarios will be defined in section . Afterwards, the secondary data collected to synthesize the investigation area for simulation will be shown in detail.

4.1 Logistics sector observed and the investigation area

A geographical region is classified as a city depending on its population, importance to the surrounding region, land mass and road network. The population is the most utilised factor for city classification; however, there is no generally accepted range, even in Europe. Germany is a major actor globally in the CEP services market. Germany has a broad and well-established parcel market and has the highest domestic parcel transport in Europe with a volume of about 3.9 billion parcels in 2020 [21]. The German CEP services industry has boomed over the past two decades, with revenue increasing more than twice as much to reach 23.5 billion Euros in 2020. Therefore, the classification of cities according to the Federal Office for Building and Regional Planning, as defined for Germany, was adopted. As a result, the Aachen city region in Germany is selected as the study area because of its structure which contains more than one of the intended city types to be studied.

The Aachen city region (known as Städteregion Aachen in German) is a special type of administrative district and is located southwest of North Rhine-Westphalia, Germany. It comprises of eight cities which are Aachen, Alsdorf, Baesweiler, Eschweiler, Herzogenrath, Monschau, Stolberg (Rhineland) and Würselen as well as the municipalities of Simmerath and Roetgen [53]. Aachen city region has a total population of 556,631 persons with an area of 706.8 square kilometres, according to 2020 data. Aachen is the most populated with 248,878 inhabitants and Roetgen is the least populated with 8,650 inhabitants according to 2020 population data from the Federal and State Statistical Offices [54].

4.2 Scenarios definition

Based on the literature review, four scenarios as logistics measures of CEP service providers for last-mile delivery are defined as follows:

- The baseline scenario entails using diesel trucks to deliver parcels directly to (private and commercial) customers from distribution centres.
- Scenario 1 entails using electric trucks to deliver parcels directly to (private and commercial) customers from distribution centres.
- Scenario 2 involves using electric trucks and e-cargo bikes along a two-step distribution process via micro-depots. Here, B2B parcels are delivered directly to commercial customers using electric trucks while B2C deliveries become a two-step process. B2C parcels are first transferred directly to micro-depots from distribution centres by electric trucks, from which the parcels are delivered to private customers using e-cargo bikes. In addition, the micro-depots are shared by the different CEP service providers, even though each CEP service provider has its own fleet.
- Scenario 3 involves using electric trucks, parcel shops and parcel lockers. Electric trucks are used to deliver B2B parcels directly to commercial customers and B2C parcels are delivered to parcel shops and lockers closest to private customers. Private customers are then required to cover a short distance to pick up their parcels from the parcel shops/lockers.

4.3 Data collection

The reference year for data gathering was 2020. Most of the information used to build the scenarios is secondary data and Table 2 summarises the relevant information concerning the data collected. Private customers refer to individuals within the study area who are potential customers for parcel delivery on a typical day. Using the synthetic population data of the Aachen city region (which contains the number of persons, their age cohort and geographical coordinates) and the corresponding share of online shoppers in the region, the number of potential private customers that will utilise CEP services is derived. Data on commercial customers are extracted from the OpenStreetMap database based on companies that receive and send parcels on a regular basis (e.g., retail business, gastronomy, universities/research and development, etc.) because there is unfortunately no available information on existing commercial customers of CEP services within the study area. The identification of potential commercial customers by means of OpenStreetMap files was adapted from the work of [57], which was designed following the German classification of economic activities. The time window for B2B deliveries is 09:00 to 18:00, which is the average working hours of most businesses.

The private freight demand per day, which is to be randomly distributed among the potential e-commerce users, is estimated based on the data sources Manner-Romberg et al. [9, 37], and [54]. [9] 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 Aachen city region. Afterwards, the freight demand per day: FD_p/wd is derived, whereby wd is working days per year, including Saturdays. The commercial freight demand per day is also estimated based on the data sources [9] and [54]. The CEP-index B2B - number of parcels per one million € of gross domestic product (GDP) per year [9] is multiplied by the GDP of the Aachen city region 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. For more information, [57] explains the data preparation in detail.

Only the major CEP service providers in Germany are considered in this research because they collectively transported 93% of the freight volume in Germany in 2020 [46]. The CEP service providers are Deutsche Post DHL, Hermes Group, DPD Group, United Parcel Service (UPS) and General Logistics Systems (GLS). The information about the distribution centres, post offices, parcel shops and parcel lockers of CEP service providers is extracted from their respective websites and reports. Micro-depots are extracted based on potential locations such as parking areas in front of supermarkets and shopping centres.

Furthermore, the road network connects the entire region and it is made of links and nodes. Each link has attributes such as length, capacity, free-flow speed, mode, and the number of lanes. The free-flow speed refers to the maximum travel speed on a given road segment when there is no congestion or other adverse conditions. The road network of the study area was extracted from the OpenStreetMap database as an OSM file, and it was then converted to an XML file to be used in the simulation. Due to the unavailability of traffic data to calibrate the road network, it is assumed that the travel speed on the road network is a function of the average congestion level associated with the study region. Hence, the average congestion for the Aachen city region is applied to estimate the travel speed in order to account for the surrounding

Table 2 Overview of data collection

Inputs	Values	Characteristics	Sources
Private customers	69,880 private customers	The synthetic population of the study area and share of e-commerce users	[54] and [59]
Commercial customers	3812 commercial customers	Businesses within the study area with a tendency to use CEP services as classified by [57]	OpenStreetMap database
Freight demand	42,801 parcels for B2C and 41,907 parcels for B2B	Estimated B2B and B2C freight demand per day for the study area	Manner-Romberg et al. [9, 37] and [54].
Distribution centres	9 distribution centres	Existing distribution centres of CEP service providers serving the study area	Websites of CEP service providers - DHL, DPD, GLS, Hermes and UPS
Parcel shops	377 parcel shops	Existing parcel shops and post offices in the study area	Websites of CEP service providers - DHL, DPD, GLS, Hermes and UPS
Parcel lockers	82 parcel lockers	Existing parcel lockers - DHL parcel station and Amazon lockers - in the study area	DHL and Amazon websites
Micro-depots	223 micro-depots	Potential micro-depot locations in the study area	OpenStreetMap database
Road network	Road network of the Aachen city region	The road network of the study area is extracted as an OSM file. The file contains the links and nodes.	OpenStreetMap database
Freight vehicles	Refer to Table 3	Type and technical specifications of vehicles to be used	[1, 2] and [8]
Emission conversion factors	Refer to Table 4	The fuel-based conversion factor of CO_2, CO, HC and NO_X	[26, 57] and Icha et al. [30]

Table 3 Vehicle characteristics of the utilised freight vehicles

Vehicle parameters	VW crafter panel van	VW e-crafter panel van	Musketier e-cargo bike
Vehicle type	Light-duty truck	Light-duty truck	Cargo bike
Fuel source	Diesel	Electric	Electric
Payload (kg)	1478	998	242
Permissible total weight (kg)	3500	3500	300
Empty weight (kg)	2022	2502	58
Range (km)	872	173	46
Maximum speed (km/h)	143	90	32

Source: Technical specifications of the diesel and electric vans are extracted from [1] and [2]. E-cargo bike features are based on [8]

traffic on the road network. This value for the Aachen city region was 26% in 2020 [58]. Consequently, the updated travel speed is as shown in the equation below.

$$\text{Updated travel speed} = \frac{\text{Free-flow speed}}{\text{Congestion rate} + 1}$$

Freight vehicles are essential because they are the means of transport used by CEP service providers to convey freight goods from distribution centres/micro-depots to customers. Light-duty trucks with a permissible total weight (ptw) of 3.5 tonnes are assumed to be the common vehicle size used for last-mile delivery. The vehicle's features aid in calculating transport costs (including fixed, variable, and personnel costs) [57]. The fixed cost of each vehicle, as shown in Table 5, is estimated based on purchasing cost, depreciation, interest costs, motor vehicle tax, insurance, etc. The variable cost of each vehicle is estimated based on depreciation, repair and maintenance costs, tyre costs and fuel costs. The personnel cost is estimated based on the average wage of drivers of the vehicles per hour (€/h) for all vehicles used.

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 [26], 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. For detailed information on the preparation of the secondary data collection for synthesising the investigation area, the reader is referred to [57].

5 Results

The simulation results are generated for a typical business day of delivery activities and are used to assess the suitability of the scenarios as a logistics measure of CEP service providers for last-mile delivery in small- and medium-sized cities. The results of the baseline scenario served as the yardstick to compare other scenarios in terms of mileage performed, the number of tours, energy consumption, transport costs and environmental impacts (CO_2, CO, HC and NO_X emissions).

5.1 Transport-related and economic KPIs

In the following section, the transport-related and economic impacts of the logistics concepts investigated in comparison to the baseline scenario will be presented and discussed in-depth.

5.1.1 Freight transport demand: number of tours

Here, a freight tour refers to all the activities performed by a driver/vehicle in the last-mile delivery process from the distribution centre and back to the distribution centre. For scenarios 1, 2 and 3, the number of tours carried out to fulfil the daily last-mile deliveries (B2B and B2C) is higher than that of the baseline scenario, as shown in Fig. 5. The number of tours fulfilled using diesel trucks in the baseline scenario is 636. In comparison to the baseline scenario, scenario 1 required 24.8% more tours, scenario 2 needed 263.7% more tours, and scenario 3 performed 21.7% more tours. Scenario 2 has the highest number of tours due to its two-step distribution process for B2C parcels. For B2C parcels in scenario 2, another tour is initiated for e-cargo bikes from the micro-depots to the private customers. As a result, 776 tours are made by electric trucks and 1,537 tours are made by e-cargo bikes. In general, the differences in the number of tours for each scenario can be related to the loading capacity of the utilised vehicles. The diesel truck model has the highest loading capacity in comparison to the electric truck and e-cargo bike models (as defined in Table 5). Therefore, more tours are required when using electric trucks and e-cargo bikes to fulfil the same quantity of daily freight demand.

5.1.2 Mileage performed

The mileage performed in the baseline scenario is 64,690.1 kilometres, whereas it increased by 8.4% in scenario 1. The increase in scenario 1 is due to more tours being fulfilled, which was prompted by the loading capacity of electric trucks compared to diesel trucks. The

Table 4 Emission conversion factors

Emission type	Conversion factor
CO_2 conversion factor - electricity (well-to-wheel)	0.375 kg/kWh
CO_2 conversion factor - diesel	2.629 kg/l
CO_2 conversion factor - AdBlue	0.238 kg/l
CO conversion factor - diesel	0.28 g/km
HC + NO_X conversion factor - diesel	1.04 g/km

Source: The emissions conversion factors are obtained from the works of [26, 57] and Icha et al. [30]

Table 5 Calculated attributes of the utilised freight vehicles

Parameters	Diesel truck	Electric truck	E-cargo bike
Maximum loading capacity (parcel units/vehicle)	160	115	30
Fixed costs (€/day)	45.498	52.385	3.135
Variable costs (€/km)	0.336	0.373	0.258
Personnel costs (€/h)	15.124	15.124	11.633
Energy consumption	0.086 l/km	0.296 kWh/km	0.0113 kWh/km
AdBlue consumption (l/km)	0.0015	–	–

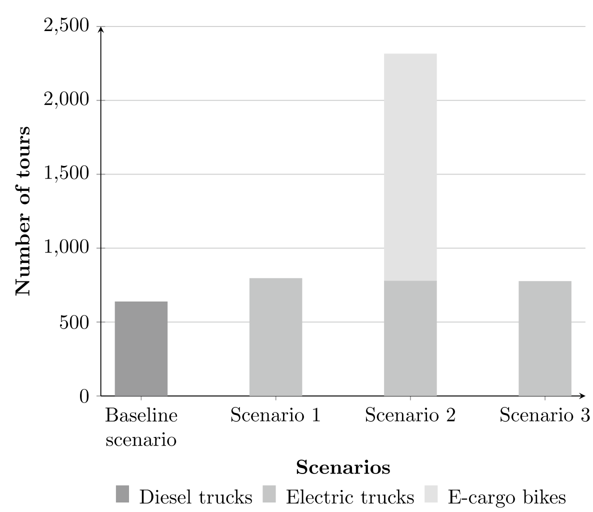

Fig. 5 Number of tours

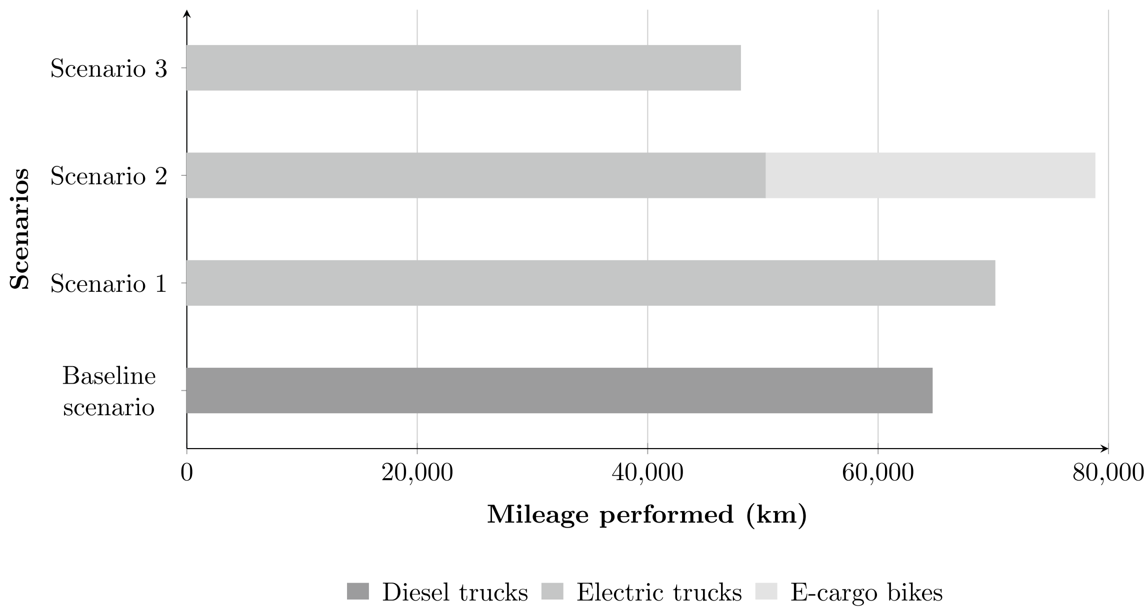

Fig. 6 Mileage performed

mileage performed increased by 21.8% in scenario 2 and decreased by 25.7% in scenario 3 when compared to the baseline scenario. In scenario 2, the significant increase in the mileage performed is due to the two-step distribution process for B2C deliveries and the lesser loading capacity of electric trucks and e-cargo bikes utilised in comparison to diesel trucks utilised, which leads to more tours being performed. In scenario 3, less distance is covered because B2C parcels are delivered to parcel shops or lockers nearest to the private customer instead of home deliveries. Thus, it reduces mileage and allows for better vehicle routing. However, the distance covered by private customers to the parcel shops/lockers in scenario 3 is not considered nor included in the total mileage performed. In scenario 2, the mileage performed by electric trucks is 50,196.5 kilometres, and that of e-cargo bikes is 28,617.8 kilometres, as can be observed in Fig. 6.

Furthermore, the average mileage per tour is 101.7 kilometres in the baseline scenario. The average mileage per tour decreased by 13.2%, 66.5% and 39% in scenarios 1, 2 and 3, respectively. The reduction in scenarios 1, 2 and 3 is because of the high number of tours performed in these scenarios, which were prompted by the lesser loading capacity of the vehicles used (electric trucks and e-cargo bikes) in comparison to diesel trucks. In scenario 2, the average mileage performed by electric trucks is 64.7 kilometres, and that by e-cargo bikes is 18.6 kilometres.

5.1.3 Energy consumption and costs

Energy consumption is an important factor which influences the total operating costs and emissions based on the fuel type. Due to the type of vehicles used in the scenarios, diesel in litres (l) and electricity in kilowatt-hours (kWh) are the energy sources considered. Hence, energy consumption is assessed using energy cost because the two energy sources have different measurement units. The energy consumptions are 5563.3 litres of diesel in the baseline scenario, 20,759 kWh of electricity in scenario 1, 15,181.6 kWh of electricity in scenario 2 (97.87% by electric trucks and 2.13% by e-cargo-bikes) and 14,223.1 kWh of electricity in scenario 3. In other words, the electricity consumption in scenarios 2 and 3 decreased by 26.87% and 31.48% respectively in comparison to scenario 1. The energy costs incurred, expressed in Euros per day, decreased by 12.5%, 36% and 40.1% in scenarios 1, 2 and 3, respectively, in comparison to the baseline scenario. Hence, scenario 3 has the lowest energy costs, as shown in Fig. 7. Scenarios 1, 2 and 3 incurred notably lower energy costs because the electricity cost per unit kWh is cheaper than one litre of diesel. Even though there is a notable increase in the number of tours performed in scenario 2 compared to scenario 1, scenario 2 incurs lower energy costs because e-cargo bikes do not consume much energy.

5.1.4 Total transport costs

The total transport costs are the sum of the fixed transport costs, variable transport costs and personnel costs per scenario. Fixed costs are not influenced by the quantity of goods or services rendered. The fixed costs incurred per day compared to the baseline scenario increased by 43.7% in scenario 1, 57.1% in scenario 2 and

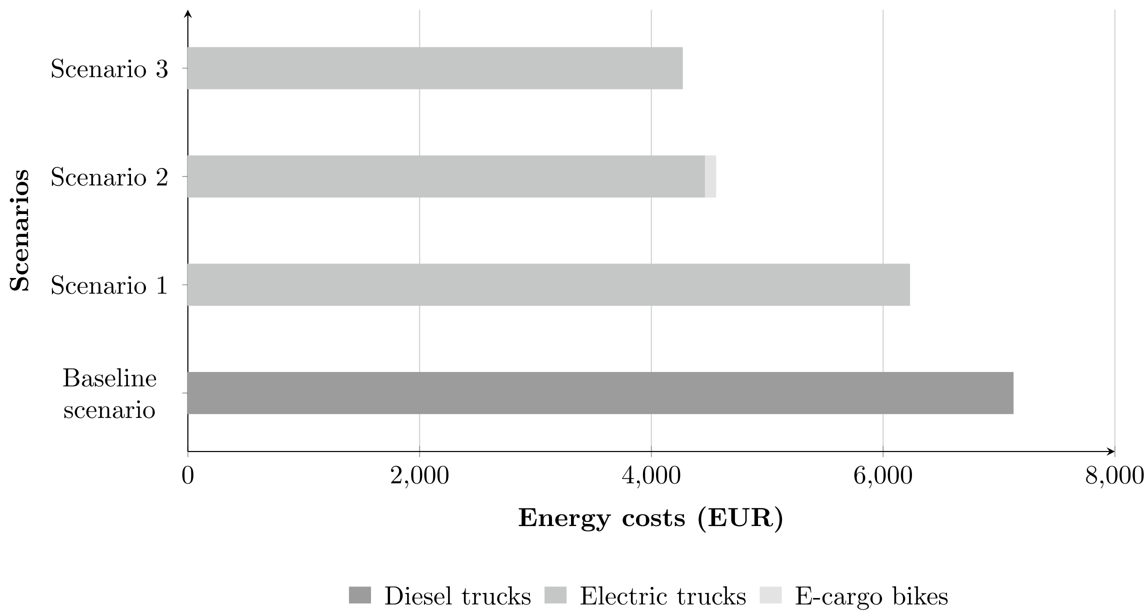

Fig. 7 Energy costs

40.1% in scenario 3. The increase in fixed costs in scenarios 1, 2 and 3 is related to the fact that electric vehicles are expensive. Variable costs are influenced by the quantity of goods or services rendered. In last-mile delivery, variable costs are dependent on mileage performed. Compared to the baseline scenario, the variable costs incurred are a 20.5% increase in scenario 1, a 20.2% increase in scenario 2 and a 17.5% decrease in scenario 3. Personnel costs are time-varying costs associated with the wages of employed persons for their services rendered in carrying out the last-mile delivery. In comparison to the baseline scenario, the personnel costs incurred are a 5.6% increase in scenario 1, an 8.6% increase in scenario 2 and a 44% decrease in scenario 3.

Scenario 3 has the lowest total transport costs per day, which is 73,795 Euros, and this is a 5.4% decrease in comparison to the baseline scenario. Scenarios 1 and 2 showed a 23.9% and 29.8% increase in total transport costs compared to the baseline scenario, respectively. Therefore, scenario 2 has the highest total transport costs, as shown in Fig. 8. The total transport costs incurred in scenario 2 is the sum of 75,082.7 Euros from using electric trucks and 26,232.1 Euros from using e-cargo bikes. It is important to note that the costs for operating and maintaining the micro-depots, parcel shops and parcel lockers are not considered in the total transport costs of scenarios 2 and 3. Furthermore, the average transport costs per tour in scenarios 1, 2 and 3, when compared to the baseline scenario, decreased by 0.8%, 64.3%, and 22.3%, respectively.

5.2 Environmental KPIs

In this section, ecological key performance indicators (emissions) resulting from the simulation results are presented. The environmental impacts of implementing each scenario as a logistics measure of CEP service providers for last-mile delivery are assessed based on the carbon dioxide (CO_2), carbon monoxide (CO), hydrocarbons (HC) and nitrogen oxide (NO_X) emissions. This is essential in ensuring that the logistics measures are not detrimental to the environment. The environmental impacts of using diesel trucks in the baseline scenario are 18 grams of CO emissions and 67.5 grams of HC and NO_X emissions. Electric vehicles do not emit CO, HC and NO_X because their combustion process is free of these harmful emissions [45]. Therefore, electric trucks and e-cargo bikes emit zero CO, HC and NO_X emissions. Hence, scenarios 1, 2 and 3 are significantly better than the baseline scenario in terms of CO, HC and NO_X emissions because they are 100% reduced. Generally, electric vehicles (electric trucks and e-cargo bikes) do not emit CO_2 emissions but the plants producing the electricity are not emission-free. Hence, the CO_2 emitted during electricity production is considered using the well-to-wheel analysis. In comparison to the baseline scenario, the CO_2 emissions in scenarios 1, 2 and 3 decreased by 46.9%, 61.1% and 63.6%, respectively. This reflects one of the benefits of electric vehicles over diesel vehicles in terms of their ecological friendly prospects as a logistics measure.

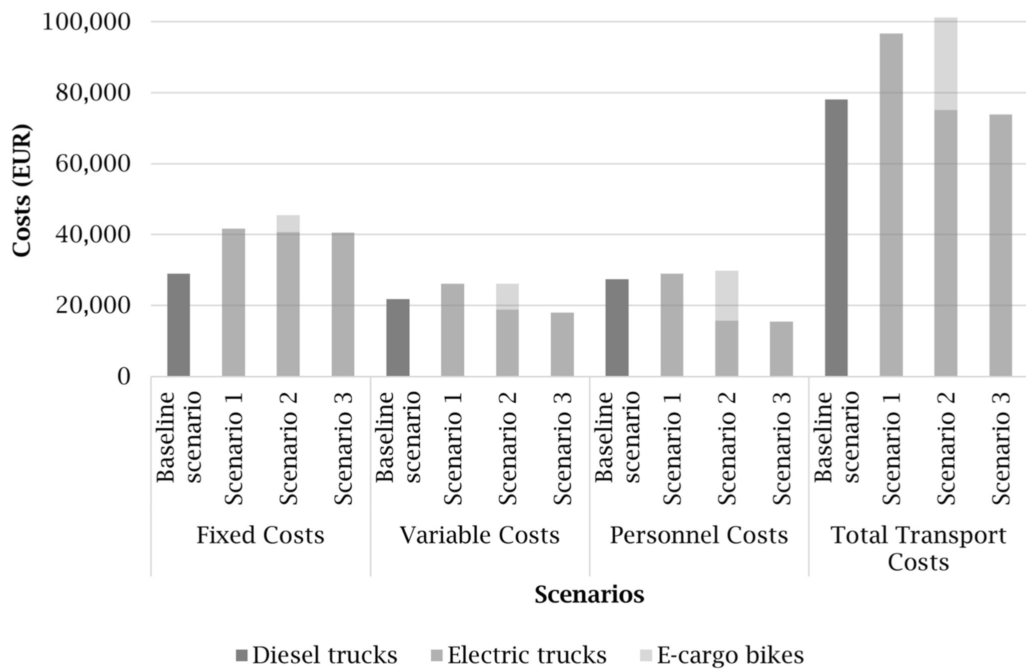

Fig. 8 Total transport costs

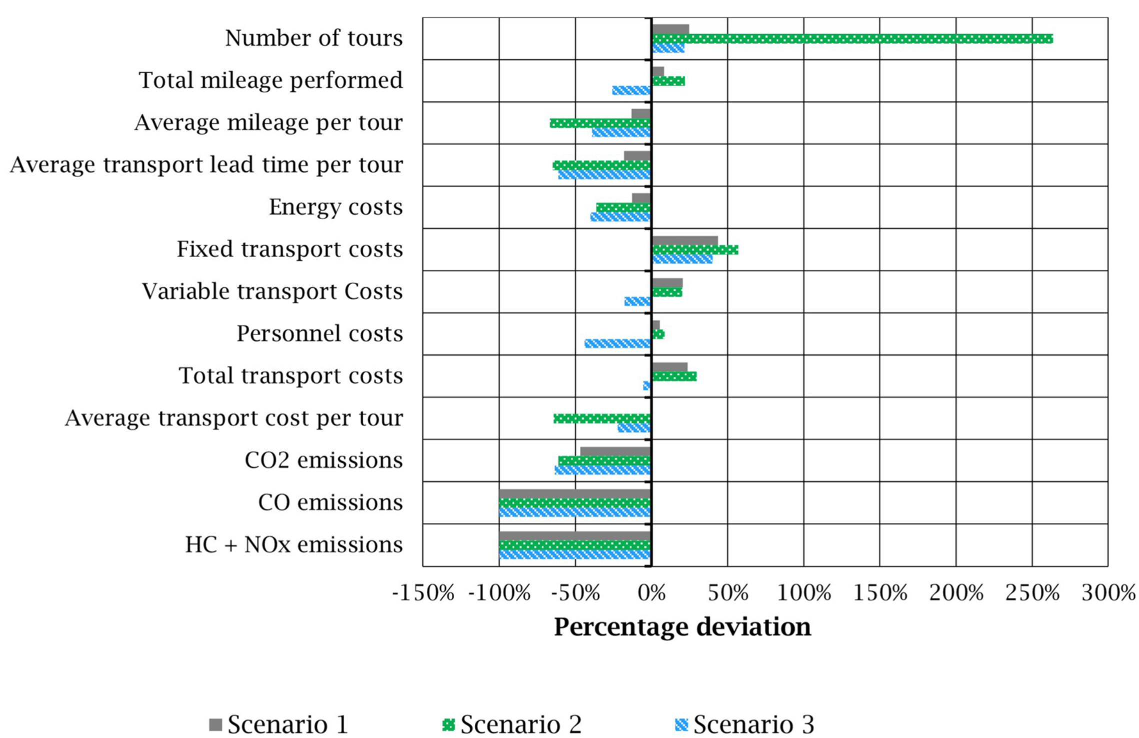

Fig. 9 Percentage deviation of the three scenarios to the baseline scenario

6 Discussion

For last-mile delivery in small- and medium-sized cities, CEP service providers need innovative approaches to reduce transport costs and emissions. Therefore, a simulation-based analysis was conducted to investigate the prospects of replacing diesel trucks with other logistics measures and vehicle technologies (i.e., scenarios). The baseline scenario is used as a yardstick to compare the other measure scenarios for each indicator under consideration and the percentage deviations are shown in Fig. 9.

Electric trucks (scenario 1) have been advocated recently as a sustainable logistics measure for last-mile delivery. Still, the use of electric trucks for last-mile delivery in small- and medium-sized cities is not cost-effective compared to diesel trucks (baseline scenario), as shown in Fig. 9. The total transport costs and its components in scenario 1, i.e., fixed costs, variable costs and personnel costs, are higher than those of the baseline scenario. More tours are also required when using electric trucks because of their lower loading capacity in comparison to diesel trucks. More tours equally resulted in more mileage performed by the electric trucks; however, the average mileage per tour decreased by 13.2%, the average transport time per tour decreased by 17.9%, and the average transport costs per tour decreased slightly by 0.8% in comparison to the baseline scenario. The average vehicle capacity utilisation per tour is 92.8%, which indicates a good usage level. In addition, the use of electric trucks only (Scenario 1) showed some advantages in terms of energy costs and emissions. The energy costs incurred are lower than those of the baseline scenario, partly because electricity is cheaper than diesel. Electric trucks have significant benefits to the environment compared to diesel trucks because they emit fewer CO_2 emissions (a 46.9% reduction) and no CO, HC or NO_X emissions.

Scenario 2 involves using electric trucks, e-cargo bikes and micro-depots for last-mile delivery. The two-step distribution process for B2C parcels led to a notable increase of 263.7% in tours performed to fulfil the daily freight demand compared to the baseline scenario. Furthermore, there is an increase of 21.8% in total mileage performed, even though an average tour covered fewer kilometres and had fewer stops when compared to the baseline scenario. Scenario 2 is also not cost-effective like scenario 1, with an increment of 29.8% in total transport cost in comparison to the baseline scenario, as shown in Fig. 9. Nonetheless, the average transport costs per tour reduced significantly (64.3%), and tours were equally completed faster than in the baseline scenario, with a 64.9% reduction in average transport time per tour. The average vehicle capacity utilisation per tour is 93.9%, which indicates a good usage level. Due to the low cost of electricity and the low energy consumption of e-cargo bikes, the cost of energy consumed decreased by 36%. In addition, scenario 2 showed significant benefits to the environment with a 61.1% decrease in CO_2 emissions and a 100% decrease in CO, HC and NO_X emissions.

Scenario 3 involves the use of electric trucks, parcel shops and parcel lockers. In scenario 3, the number of tours increased by 21.7% compared to the baseline scenario but there was a notable reduction in mileage performed, energy costs, total transport costs, and environmental impacts. Compared to the baseline scenario, there is a 25.7% decrease in mileage performed, a 40.1% decrease in energy costs, a 5.4% decrease in total transport costs, a 63.6% decrease in CO_2 emissions, and a 100% decrease in CO, HC and NO_X emissions in scenario 3. Though fixed costs increased by 40.1% compared to the baseline scenario, variable and personnel costs decreased by 17.5% and 44%, respectively. As a result, scenario 3 is the most cost-effective logistics measure for last-mile delivery in small- and medium-sized cities with significant environmental benefits. In addition, the average mileage per tour decreased by 39%, the average transport time per tour decreased by 60.9%, and the average transport costs per tour decreased by 22.3% in comparison to the baseline scenario. The average vehicle capacity utilisation per tour is 95.2%, i.e. the electric trucks were well utilised.

7 Conclusion and outlook

Despite the general notion that diesel trucks are the most practical solution for last-mile delivery in small- and medium-sized cities, it is important to establish sustainable logistics practices in small- and medium-sized cities because of operational efficiency and environmental concerns. Therefore, a simulation-based analysis was conducted by means of the microscopic, agent-based transport simulation MATSim and the linked route optimisation Jsprit to examine the viability of potential logistics measures available to CEP service providers for last-mile delivery in small- and medium-sized cities. The result revealed that electric trucks are not cost-effective as a stand-alone logistics measure for last-mile delivery in small- and medium-sized cities. The use of only electric trucks leads to more tours, more mileage performed, and higher transport costs due to their lesser loading capacity in comparison to using diesel trucks. Notwithstanding, electric trucks are more advantageous for the environment than diesel trucks because they emit fewer CO_2 (46.9% reduction based on well-to-wheel analysis) and zero CO, HC and NO_X emissions. In addition, electric trucks can be integrated with other sustainable logistics measures such as e-cargo bikes, parcel shops and parcel lockers for operational efficiency, as modelled in scenarios 2 and 3.

The integration of electric trucks with e-cargo bikes and micro-depots for last-mile delivery yielded a reduction of 36% in energy costs, 61.1% in CO_2 emissions, and 100% in CO, HC and NO_X emissions, as well as an increment of 21.8% in mileage and 29.8% in total transport costs, in comparison to diesel trucks. Hence, the mix of electric trucks with e-cargo bikes and micro-depots for last-mile delivery in small- and medium-sized cities is not good economically for the CEP service providers, but it is good for the environment. Contrary to other studies such as [36] among others, it was observed that the use of e-cargo bikes and micro-depots did not lead to a reduction in total transport costs, although this could be due to several reasons. Perhaps the performance of using a mix of electric trucks with e-cargo bikes and micro-depots can produce better results in small- and medium-sized cities when more micro-depots are strategically positioned within the study area.

The use of electric trucks in conjunction with parcel shops and parcel lockers is a viable logistics measure and is cost-effective for last-mile delivery of CEP services. In addition, there is a notable reduction of 25.7% in mileage performed, 5.4% in total transport costs, 63.6% in CO_2 emissions, and 100% in CO, HC and NO_X emissions in comparison to diesel trucks for last-mile delivery. Hence, the mix of electric trucks, parcel shops and parcel lockers (scenario 3) is the best logistics measure for last-mile delivery in terms of mileage performed, energy consumption, total transport costs, and environmental impacts. Also, it offers a longer duration for parcel collection than home delivery. However, private customers' willingness to pick up parcels in a nearby parcel shop/parcel locker is essential for a successful operation.

Though the results of the modelled scenarios can be transferred to other cities, there may be little variations in other small- and medium-sized cities due to differences in the study area's condition regarding the number of micro-depots, parcel shops and parcel lockers. In general, the mix of sustainable logistics measures is a feasible solution for last-mile delivery in small- and medium-sized cities such as the municipalities in the Aachen city region. Hence, CEP service providers should switch to a mix of sustainable logistics measures such as electric trucks with parcel shops/parcel lockers. The mix of sustainable logistics measures would yield better operational efficiency for last-mile delivery in small- and medium-sized cities and fewer emissions than diesel trucks. Total transport costs can be reduced by at least 5.4% and CO_2 emissions by at least 61%.

The limitations and outlook of this paper are as follows:

- In scenario 3 (electric trucks with parcel shops and lockers), the time costs of private customers going to pick up their parcels were not considered because they are less relevant from a CEP service provider's perspective.
- The costs associated with operating and maintaining facilities such as micro-depots, parcel shops and parcel lockers are not considered.
- The impacts of varying the number of micro-depots on last-mile delivery were not studied. However, further studies can be done on this in the context of small- and medium-sized cities.

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Data availability
The sources of the data are stated in Table 1 of the paper. Some of the data are available online from the sources mentioned, while others cannot be shared, such as the synthetic population data of the study area, due to data protection.

Declarations

Competing interests
The authors declare that they have no competing interests.

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