Chair of Transportation Systems Engineering
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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 of the Aachen City Region

A thesis presented in part fulfilment of the requirements of the Degree of Master of Science in Transportation Systems at the TUM School of Engineering and Design, Technical University of Munich.

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Declaration

I hereby confirm that the presented thesis work has been done independently and using only the sources and resources as are listed. This thesis has not previously been submitted elsewhere for purposes of assessment.

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Abstract

The e-commerce sector's rapid expansion has led to an increase in last-mile delivery activities both within and across cities, fuelling the growth of the courier, express, and parcel (CEP) services industry. Even though last-mile delivery is the costliest and least efficient segment of the entire logistics system, CEP service providers are faced with the challenge of offering fast and flexible delivery at competitive pricing. For last-mile delivery in small- and medium-sized cities, CEP service providers tend to be less innovative and consider diesel trucks the most viable logistics measure. This study analyses the alternative logistics measures of CEP service providers for last-mile delivery in small- and medium-sized cities, as well as their impacts on the delivery services, especially the resulting transport costs and environmental impacts. An empirical analysis was conducted using the agent-based transport simulation MATSim and the integrated logistics behavioural model jsprit to analyse the feasibility of selected logistics measures of CEP service providers. 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, electric trucks can still be a viable logistics measure for last-mile delivery when combined with other sustainable logistics measures, such as e-cargo bikes with micro-depots or parcel shops and parcel lockers. In comparison to using diesel trucks for last-mile delivery in small- and medium-sized cities, using electric trucks and e-cargo bikes in combination with micro depots showed a reduction of 14.2% in total transport costs, 37.6% in total freight mileage, 84.1% in CO_2 emissions, and 100% in CO, HC and NO_X emissions. Using parcel shops and parcel lockers combined with electric trucks showed a significant reduction of 31.2% in total transport costs, 60.4% in total freight mileage, 80.6% in CO_2 emissions, and 100% in CO, HC and NO_X emissions. For last-mile delivery in small- and medium-sized cities, CEP service providers should switch to mixed sustainable logistics measures that are more effective than diesel trucks in reducing operating transport costs and negative environmental impacts.

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List of Abbreviations

CEP	Courier, Express and Parcel Services
CO	Carbon monoxide
CO_2	Carbon dioxide
GHG	Greenhouse gas
HC	Hydrocarbons
NO_X	Nitrogen Oxides
PM_{10}	Particulate matter

1. Introduction

Over the last decades, the total volume of freight transportation that goes into and out of cities has grown simultaneously with urban population expansion and e-commerce growth. As a subsector of freight transportation, the courier, express and parcel (CEP) services market has experienced a similar growth pattern. The importance of the CEP services market was strengthened further in 2019 - 2021 during the global pandemic caused by the coronavirus disease (COVID-19). As a result, the global parcel volume reached 131.2 billion parcels in 2020, representing an increase of 27 per cent compared to 2019 (Statista, 2021). This volume is projected to increase continuously by at least 11 per cent annually until 2026 and possibly beyond. With a domestic parcel transport of approximately 3.9 billion parcels in 2020, Germany has a broad and well-established parcel industry, making it the largest in Europe. Over the last two decades, the CEP services market in Germany has experienced a booming period, growing more than two times in revenue, reaching 23.5 billion Euros in 2020. A 2021 study estimated that the CEP services market in Germany could exceed 32 billion Euros by 2025, even after considering the impact of the coronavirus pandemic on the market (Statista, 2021).

The growth of the CEP services market, like the global freight market, has been propelled by e-commerce growth, resulting in a corresponding increase in delivery activities within and across cities. This implies that the increase in the total freight volume, coupled with increasing demand for fast delivery by customers at the lowest possible cost, has increased the total number of deliveries, usually managed by a large variety of transportation companies such as Amazon, DHL, DPD, UPS, etc. Hence, these transportation companies, including CEP service providers, are faced with the challenge of providing fast delivery at reasonable prices. This study analyses the last-mile delivery challenge from a courier, express and parcel (CEP) service providers' perspective in small- and medium-sized cities that often have middle to low population density and dispersed spatial distribution.

1.1. Motivation

Over time, CEP service providers have introduced several delivery measures/concepts to address the growing demand for quick delivery services to improve delivery performance and lower transportation costs, particularly in the last-mile. In 2018, a study on 500 global grocery retailers and consumer product firms revealed that the last-mile transport cost constituted 41 per cent of the total supply chain costs (Capgemini, 2019). Therefore, CEP service providers are shifting to sustainable logistics measures for last-mile delivery in large and dense cities. On the other hand, CEP service providers are less innovative and see diesel trucks as the most viable and profitable logistics measure in small and medium-sized cities. This approach could be counterproductive and, thus, warrants a study in the context of small- and medium-sized cities. Similarly, studies on the last-mile delivery of CEP services often focus on dense cities such as Munich, Berlin, Paris, etc. These highlighted challenges motivate the analysis of last-mile delivery concepts that CEP service providers can implement and their impacts regarding transport costs per tour, the performance of the delivery service and greenhouse gas (GHG) emissions.

1.2. Objective and Research Questions

This study aims to analyse the logistics measures of CEP service providers for last-mile delivery in small- and medium-sized cities, as well as their impacts on the delivery services, especially the resulting transport costs and environmental impacts.

Hence, the research questions are:

- What logistics measures have CEP service providers implemented for last-mile delivery?
- What impacts do the selected logistics measures of CEP service providers have on last-mile delivery, especially the resulting transport costs and environmental impacts in small- and medium-sized cities?

1.3. Research Structure

The study aims to provide an empirical analysis of the quantitative impacts of logistics measures of CEP service providers for last-mile delivery in the context of small- and medium-sized cities. Small- and medium-sized cities are considered because of their particular spatial structure, characterised by low population density and sparsely distributed delivery destinations. The research structure to achieve the objectives are as shown in Figure 1.1. The first chapter contains an introduction to the research as well as the research questions and objective of the study. The second chapter discusses the relevant literature on the state-of-the-art concerning freight transportation, courier, express and parcel (CEP) services and the logistics measures of CEP service providers.

The third chapter discusses the methodology used, i.e., MATSim and Jsprit functionalities, as they apply to this research in detail, the procedures for setting up the simulation, the tools used, the system limitations and the assumptions made. Chapter four explains the case study area, the data preparation processes and the scenarios evaluated in this research. In chapters five and six, the important results are presented, and insights from the results are discussed. Finally, chapter seven contains the conclusion and research limitations.

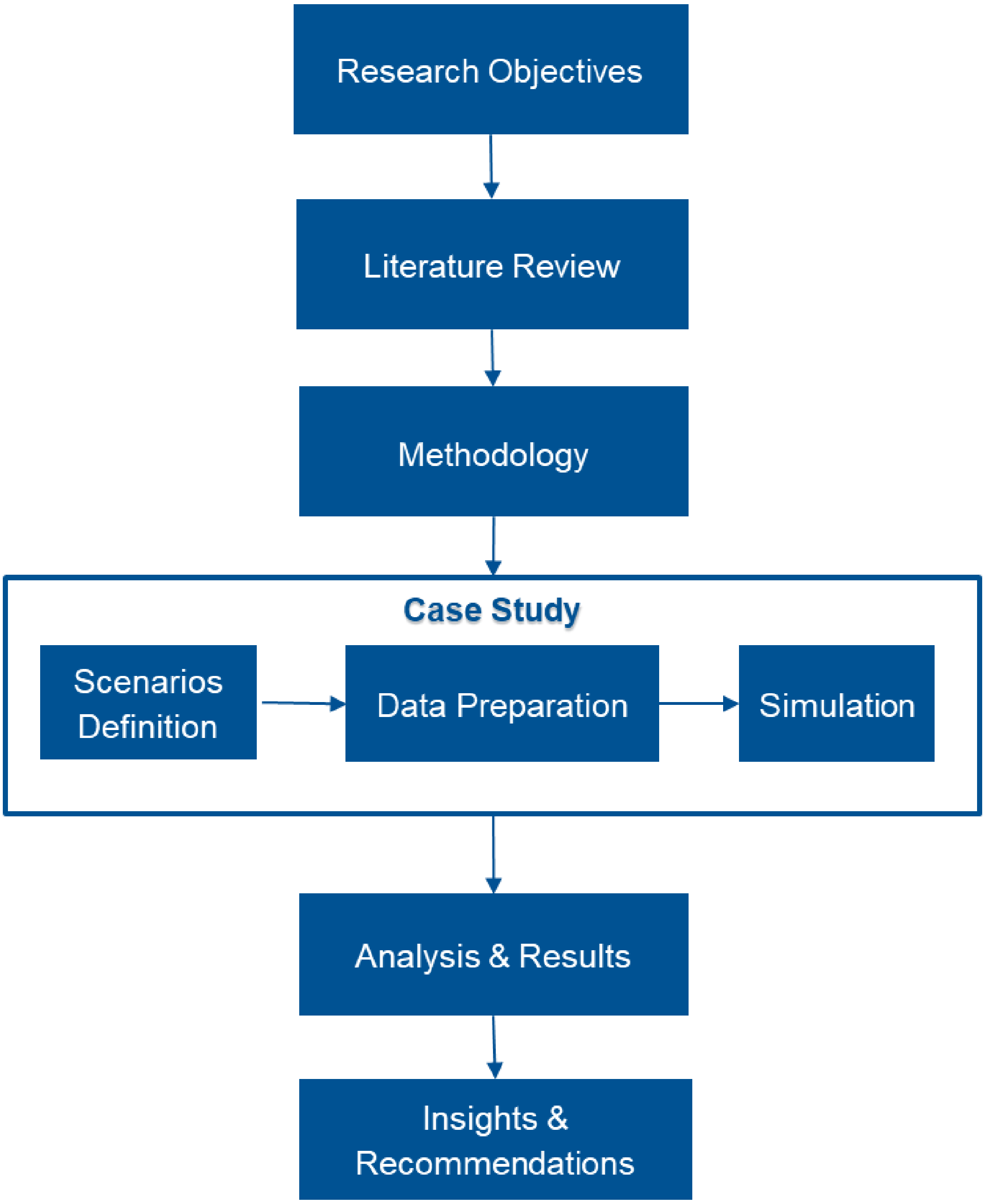


Figure 1.1 Research Structure

2. Literature Review

The freight transportation industry has been growing fast since the emergence of e-commerce and has been an important one in the last decades in terms of the transportation of goods across regions. The freight transportation industry is a superstructure with submarkets, such as CEP transport, general cargo and cargo transport, which have also been growing significantly. However, these submarkets differ from one another based on specific features. The features that differentiate the submarkets of the freight industry include shipment size, means of transport, loading units, transport network structures, functional interrelationships, type of clients and transport concept (Thaller, 2018).

2.1. Courier, Express and Parcel (CEP) Services

The Courier, Express and Parcel services, often called CEP, can be described as logistics and postal services providers that specialise in moving parcels/packages. The CEP services industry is a submarket of the freight transportation industry that deals with small goods/parcels. These parcels vary in size and weight, from small packages such as letters to heavy items weighing 30 kilograms. Road transportation remains the dominant mode of freight transportation, especially on the last-mile leg. The mode of transport explored on the main carriage depends on the distance between origin and destination, shipment size and customers' choice of service with respect to desired delivery period and willingness to pay. The characteristics of CEP services are highlighted in Table 2.1 below.

Table 2.1 Characteristics of CEP Transport

Characteristics	CEP Transport
Transport objects	Small goods
Shipment sizes	2 - 31.5 kilograms
Client industries	Business-to-Business (B2B), Business-to-Consumer (B2C), Consumer-to-Consumer (C2C)
Loading units	Package units, pallets
Means of transport	Cargo bikes, trucks with a permissible weight of 3.5 to 7.5 tonnes for local transport (pre-carriage and onward carriage), trucks with a permissible weight of 7.5 to 40 tonnes or aircraft for long-distance transport in the main carriage
Transport mode	Road, Air
Functional connections	Local, regional, and long-distance transport
Transport concept	Direct delivery, groupage transport
Transport network structures	Direct transport network, hub and spoke network
Transport chain	Pre-carriage, main-carriage and post-carriage

Note: Adapted from the work of Thaller (2018)

The CEP industry is the most dominant in logistics and one of the fastest-growing industries globally (Schröder et al., 2015). The characteristics of CEP transport help differentiate it from other submarkets of the freight transportation industry. Private household and retail demand in urban agglomerations account for most of its drivers. Therefore, the freight transport demand and tours conducted by the CEP service providers are influenced by the delivery needs of private persons and businesses. The segments of CEP services are Business-to-Business (B2B), Business-to-Consumer (B2C) and Consumer-to-Consumer (C2C). Although, the volumes of B2B and B2C are often more noteworthy in terms of total share when compared to C2C operations. CEP service providers provide courier services, express services and parcel services. These three types of services appear similar but differ in terms of weight, delivery time, speed, and type of accompaniment. Table 2.2 highlights the crucial differences between these services offered by CEP service providers.

2.1.1. CEP Services in Germany

The positive impact of the CEP services has been significant in recent years both on a global and national level, in the case of Germany. Germany has an extensive and well-established parcel market and has the highest domestic parcel traffic in Europe, with a volume of about 3.9 billion parcels in 2020 (European Commission, 2021). It is the fifth in the world regarding global parcel shipping volume after China, the United States, Japan, and the United Kingdom (Bowes, 2021). 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. Even after accounting for the effects of the coronavirus pandemic on the German CEP market, a study forecasts that the market might surpass 32 billion Euros by 2025 (Statista, 2021). The CEP services industry also experienced rapid growth due to government-imposed restrictions during the pandemic. As a result, people had to make many online purchases which were delivered to their homes.

Germany’s major CEP service providers are Deutsche Post DHL, Hermes, DPD, United Parcel Service (UPS) and General Logistics Systems (GLS). The CEP services market has benefited Germany by boosting employment, revenue generation and the attractiveness of investors. The parcel services have a higher share of 85.2 per cent of the total number of parcels in the CEP services market in Germany in 2020 (BIEK, 2021). Hence, it generated almost three times the revenue of courier services or express services. However, it is equally important to consider the induced last-mile problems from increased online shopping and the drawbacks of transportation caused by CEP services within the cities. These detrimental effects, primarily affecting the environment, include noise pollution, air pollution, traffic congestion and greenhouse gas (GHG) emissions. Figure 2.1 displays the revenue development of the CEP services market and the GDP triggered by the CEP services market in Germany from 2016 to 2020 in million Euros (BIEK, 2021).

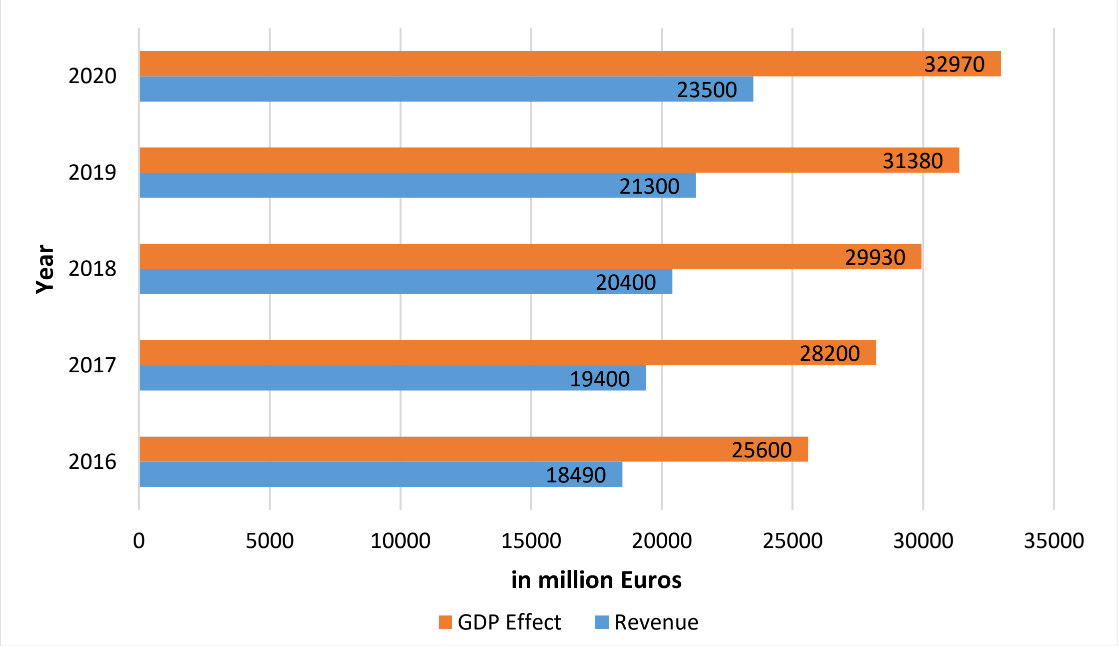


Figure 2.1 CEP Services Market Performance in Germany

Note: Data adapted from BIEK (2020)

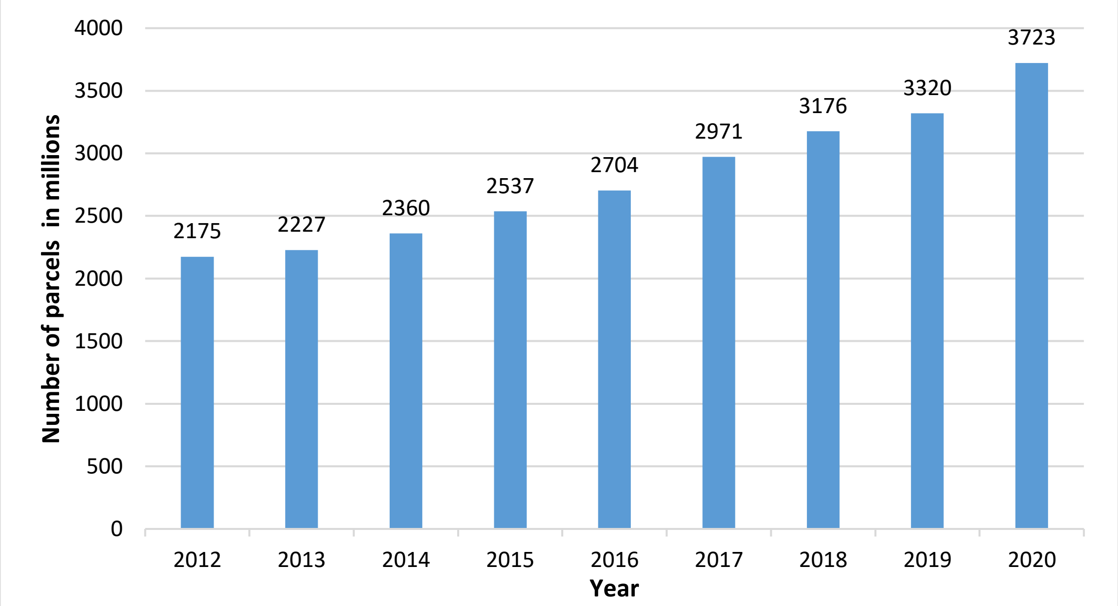


Figure 2.2 CEP Services Market Volume in Germany

Note: Data adapted from BIEK (2020)

Table 2.2 Characteristics of CEP Services

Characteristics	**Courier Services**	**Express Services**	**Parcel Services**
Transport objects	Documents, data carriers, highly sensitive small parts, spare parts or samples	Documents, general cargo	General cargo
Shipment sizes	Consignment weight up to 1.5 kg	Consignment weight up to 31.5 kg (flexible weight)	Consignment weight up to 31.5 kg (flexible weight)
Means of transport	Cargo bikes, trucks with a permissible weight of 3.5 to 7.5 tonnes	Cargo bikes, trucks with a permissible weight of 3.5 to 7.5 tonnes for local transport; trucks with a permissible weight of 7.5 to 40 tonnes or aircraft for long-distance transport	Cargo bikes, trucks with a permissible weight of 3.5 to 7.5 tonnes for local transport; trucks with a permissible weight of 7.5 to 40 tonnes or aircraft for long-distance transport
Functional connections	Local and regional transport	Local, regional, and long-distance transport	Local, regional, and long-distance transport
Operational area	Local, regional and national areas of operation	National and international areas of operation	National and international areas of operation
Transport network structures/Transport concept	Predominantly direct delivery without fixed networks and lines	Hub and spoke network with groupage transport	National and international hub and spoke network with groupage transport
Transport time	Delivery on the same day or by individual agreement	Fast, day- and time-certain delivery as well as door-to-door service (same day, next day and overnight delivery)	National delivery time: 1 - 2 days; international delivery time: 1 week
Level of service	Personal and direct accompaniment of the consignment or with the help of electronic aids	Transport of individual consignments without personal accompaniment; deadline guarantee for the customer	No fixed agreed delivery times, no deadline guarantee for the customer
Company size	Small businesses	National medium-sized and large-scale international enterprises	Large international companies

Note: Adapted from the work of Thaller (2018) and BIEK (2020)

2.2. Domains of Urban Logistics

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 transport chains are pre-carriage (pickup or first leg), main-carriage and post-carriage (last-mile delivery or last leg), as depicted in Table 2.1. To better clarify the various functionalities within these transport chains, the work of Cardenas et al. (2017) on the typology of urban logistics was adopted. They analysed 90 important scientific works related to logistics based on their objectives, methodology, research subject and scope to distinguish the various domains of goods distribution within the urban environment. They argued that many works of literature have studied and assessed logistics in the urban environment at different scopes, using attributes such as goods characteristics, vehicle movement and goods deliveries without a general framework.

Cardenas et al. (2017) constructed a typology and framework to guide future studies and identified three urban logistics areas to define each domain's systematic thresholds. These domains are city logistics, urban goods distribution and last-mile delivery and collection. They are subclasses of urban logistics, which is also known as urban freight transportation or freight transportation (Cardenas et al., 2017; Bosona, 2020). Each domain features also depict the extent and responsibility of logistics operations' actors, customers/consumers, logistics service providers and public stakeholders (authorities and governments).

2.2.1. City Logistics

City logistics is an important subclass of urban freight transportation that focuses on the interconnection between the logistics system, citizens' well-being, and the implementation of public policies on urban logistics. It involves the decision-making processes of public authorities in initiating measures to improve the inhabitants' standard of living. The government cannot simply stop transportation because of its negative externalities. Instead, they propose measures that help mitigate or eliminate the negative externalities and monitor and evaluate the implementation of the measures of the concerned party, in this case, the logistics service providers. An example is the establishment of low-emission zones in most urban cities across the world, to prevent specific categories of vehicles from entering the city centre due to the concerning emission levels of the vehicles.

Aggregate models and multi-criteria analysis are often explored when modelling city logistics because of their large scope and the interconnection elements between actors. The analysis key performance indicators are qualitative variables that help policymakers' decision-making. City logistics seeks to manage the relationships between the movement of goods into the city to improve the quality of life, its inhabitants' well-being, and sustainability. Other policy measures proposed by policymakers are vehicle weight and size restrictions, restrictions on vehicle type, congestion charging, etc.

2.2.2. Urban Goods Distribution

Urban goods distribution can be defined as *the transport of goods by means of a wheeled vehicle, and the activities related to this transport towards or within an urban environment* (Fernandez-Barcelo & Campos-Cacheda, 2012). Urban goods distribution refers to the process of improving the distribution of goods within, from, and to urban regions. It typically takes into account how freight enters the city, the consolidation and sorting facilities used, the cost of these activities and their impacts, as well as the implemented public policies to regulate urban logistics with respect to the impact this has on commuter traffic and sustainability. Here, the functional scope includes network design, logistics services and infrastructure alternatives that increase sustainability and efficiency.

Urban goods distribution is the mid-term planning domain of urban logistics that involves the innovation of solution measures that enable logistics service providers to comply with policy measures imposed by public authorities. For instance, logistics service operators use electric vehicles (electric vans, trucks or e-cargo bikes) to comply with low-emission zones' restrictions. That is, it involves the analysis of solutions to comply with the policies set by policymakers. The subfields of urban goods distribution are transport modes and shifts, network configuration, data collection, disaggregate models, and policy evaluation. The typical research methodologies are agent-based simulation, transport simulation and mathematical modelling. The end users of the proposed solutions for urban goods distribution are the set of logistics service providers, supply chain and resource managers.

2.2.3. Last-mile Delivery and Collection

Last-mile delivery and collection is the third domain of urban logistics. The last-mile delivery and collection can be defined as *the final leg in a business-to-consumer delivery service whereby the consignment is delivered to the recipient, either at the recipient's home or at a collection point* (Gevaers et al., 2011). The 'collection' part refers to the first leg in a business-to-business, business-to-consumer and consumer-to-consumer delivery service, where the consignments/parcels are picked up at the supplier's location in the case of B2B or B2C or dropped at a post office in the case of C2C for onward carriage to the specified destination. It aims at operational efficiency with emphasis on profitability, effective time management, travel distance and operating costs instead of citizens' well-being like in city logistics (Gevaers et al., 2011; Cardenas et al., 2017; Apostolopoulos & Kasselouris, 2022). The typical research methodologies applied here are optimisation and mathematical modelling to manage daily operations (i.e., short-term planning). Logistics service providers are the end users of last-mile delivery and collection solutions. However, the emphasis hereafter is on last-mile delivery due to its relevance to this research.

The term 'last-mile' is subjective because the final leg of a delivery operation depends on the distribution network and geographic layout. Last-mile delivery is influenced by structural elements (like the transportation system, location and size of distribution centres), supply chain sites, and commercial and market factors (like freight demand and transportation 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 (Apostolopoulos & Kasselouris, 2022). From a CEP service provider's perspective, the last-mile delivery does not include the long-haul transportation of the goods to the local distribution centre/depot; instead, it involves the final delivery from the local distribution centre to the final recipient of the parcels. The problems associated with a last-mile delivery start after the packages have arrived at the local distribution centres and have been sorted and ready for loading to final destinations.

The most critical factors in last-mile delivery regarding the movement of traffic within cities and sustainable delivery have to be analysed and understood in order to assess transport policies and logistical strategies of CEP service providers (Dabidian et al., 2016). Due to several factors, last-mile delivery is considered the costliest and least efficient segment of the logistics chain. A study on 500 grocery retailers and consumer product firms from the Netherlands, Germany, France, the United Kingdom and the United States revealed that last-mile delivery cost is 41 per cent of the total supply chain costs (Capgemini, 2019). The cost share of the last-mile varies depending on the region and delivery context, yet the last-mile delivery has the highest percentage of the total supply chain costs. Customer service is crucial to the effectiveness of CEP service providers, and so is cost reduction in order to stay under budget and boost profitability. Transport costs are influenced by distance-related costs (such as fuel consumption, tyre replacement and maintenance), time-related operating costs (such as truck driver wages) related to handling activities, and fixed costs (e.g., depreciation, insurance and taxes etc.). Together, these costs produce a total cost per unit parcel allocated to each route or trip.

The vehicle routing problem is a common problem for logistics service providers, and each logistics service provider chooses the best vehicle algorithm that serves their operation network. Different vehicle algorithms have been proposed by researchers using mathematical modelling. They have been adopted by logistics service providers to enhance their freight delivery operations and identify adverse effects of each routing option. CEP service providers aim to optimise their freight delivery operations by ensuring swift delivery times, minimising travel distance and transport costs, and increasing revenue (Dabidian et al., 2016; Bosona, 2020). The travelled distance is an important factor as it is associated with costs for the CEP service provider, delivery time for the customers, and emissions concerns for the public authority.

Externalities of last-mile delivery also include not-at-home deliveries, failed deliveries, security, bad weather, the need for consolidation centres, availability of parking spaces at the recipient's location, roadworks, and complex traffic situations, among others (Gevaers et al., 2011; Cardenas et al., 2017; Deutsche Post DHL Group, 2020). For instance, in-home deliveries, drivers must ensure that the parcels are received by the recipient or a member of their household, especially for sensitive packages, to secure the delivery. Also, deliveries requiring the recipient's signature as confirmation may end up as failed delivery attempts if the recipient is not at the stated location at the time of delivery. Additional measures to ensure the safe delivery of parcels to the recipient might be necessary for not-at-home deliveries. All these externalities affect logistical performance, transport costs and environmental emissions. Demand uncertainty is equally a concern, especially in small cities, because inadequate freight demand may lead to ineffective use of vehicle capacity, more transport costs, fewer benefits, and higher emissions per parcel.

The efficiency of the last-mile is influenced by the quality of the service, the transportation cost, and its environmental impact. It is also closely tied to the operation region's location and the local market's needs (Apostolopoulos & Kasselouris, 2022). Therefore, CEP service providers need to assess the available logistics measures for last-mile delivery before implementing a measure to achieve operational efficiency, considering freight demand quantity and spatial features of the geographical location. This assessment aids CEP service providers in decision-making on what vehicle type to utilise, what delivery method to implement, whether there should be a collaboration with other competitors and at what level, if any, etc. Some of the key indicators used in the assessment of last-mile delivery operations regarding operational efficiency and environmental impacts are total transport costs, number of vehicles utilised, total distance travelled, fuel consumption, number of stops, operating time windows and GHG emissions (Cardenas et al., 2017; Bosona, 2020).

2.3. Measures of CEP Service Providers on the Last-Mile

Freight delivery activities also rise as e-commerce does. Even so, more last-mile delivery trips into cities have been triggered by the rising need for quick delivery, on B2B deliveries due to businesses' just-in-time and agile strategies as well as on B2C and C2C deliveries due to people's interests (Cardenas et al., 2017). CEP service providers have implemented various measures to address the issues of urban goods distribution to improve service efficiency and revenue, comply with government regulations, reduce costs, promote their brands, support the reduction of emissions, etc. Some of these measures have been initiated by the logistics service/CEP service providers, and others have been imposed on them by public authorities. These measures include logistics and policy measures, which may be technologically aided. The CEP industry is not an exception to the widespread adoption of technological solutions to enhance operational efficiency, security, organisational productivity and customer satisfaction.

The recent preference for last-mile delivery is not only about delivery speed, but also about ease of delivery. Delivery time is a major concern, and customers now expect to be able to choose when, where and how their parcels are delivered, i.e., a faster and more flexible delivery. This challenge has created a trend towards urban localisation enabled by service stations, parcel lockers, cargo bike delivery, electric vehicles, etc., thus, shortening the last-mile. In addition, logistics service providers are paving the way for more novel and inventive solutions, such as crowdsourced deliveries and other decentralised alternatives (Euromonitor International, 2018).

The demand for quick parcel delivery has grown recently. However, customers are unwilling to pay for the additional costs that would enable CEP service providers to offer innovative delivery methods, investments in green transport vehicles, expansion of the delivery network, sustainable technologies and improved logistics performance (BIEK, 2020). According to the BIEK study on the courier, express and parcel service industry in Germany, some customers are unwilling to pay extra for alternative delivery concepts in the B2C segment of the CEP service industry. The logistics measures implemented or proposed for last-mile delivery of CEP services are identified based on their delivery types (Gevaers et al., 2011; Narayanan & Antoniou, 2021). There are mainly two delivery types, and they are direct delivery and indirect delivery.

Direct Delivery

In last-mile operation, direct delivery is the straight transporting of parcels from the supplier’s central depot or local distribution centre to the final customer. It refers to handling the parcel to the final recipient by the CEP service provider without third-party involvement. This type of delivery can be carried out by an employee of the CEP service provider or autonomous vehicle without the recipient covering any extra 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 transhipment.

Indirect Delivery

In a last-mile delivery operation, indirect delivery is the type of delivery that involves a third party between the CEP service provider and the final recipient of the parcel. This third party could be a small retail business registered with the CEP service providers as parcel shops, built parcel lockers, post offices, or outsourced firms/persons (crowdsourcing). CEP service providers sometimes explore indirect delivery options because few customers are not within their existing delivery network or as a measure to tackle the high seasonal demand for delivery service by outsourcing. This type of delivery is sometimes associated with lengthy delivery periods, more operating costs, several transfers and difficult tracking, yet it sometimes proves cost-effective (Gevaers et al., 2011). For instance, outsourcing deliveries can be cheaper than expansion or getting new personnel and vehicles to deal with the seasonal increase in demand for delivery services. Indirect delivery may require the final recipient to cover some distance to collect the parcel.

CEP service providers have implemented several last-mile delivery methods to transport parcels from distribution centres to final customers, as shown in Figure 2.3.

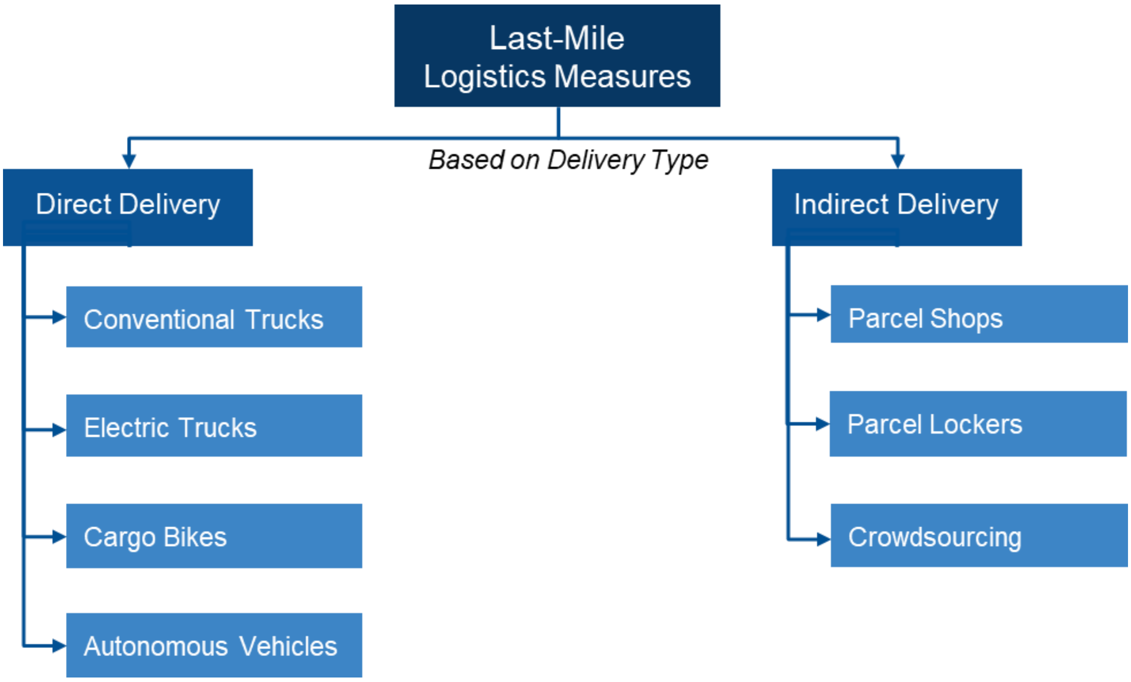


Figure 2.3 Logistics‘ Measures of CEP Service Providers on the Last-Mile Delivery

2.3.1. Conventional Trucks

Diesel vehicles with internal combustion engines have been the traditional means of transporting goods from the origin (e.g., distribution centres) to the final recipients, which could be private persons or commercial customers over the last decades. Some of these conventional vehicles use premium motor spirit (also known as petrol or gasoline); however, diesel remains the most utilised power source for commercial vehicles with internal combustion engines because of its cost benefits over gasoline. However, it has been noted that both diesel- and gasoline-powered delivery vehicles emit alarming levels of CO_2 into the atmosphere (Bac & Erdem 2021; Mehmedi 2021).

The diesel trucks utilised for CEP services have varying permissible weights from 3.5 to 70 tonnes, depending on the service rendered and the supply-chain section performed. Smaller trucks are more adaptable and fuel-efficient in cities, but bigger vehicles are needed to keep up with demand. The usage of smaller trucks results in increased emissions and higher transportation costs (Apostolopoulos & Kasselouris, 2022). Light diesel trucks with a total permissible weight of 3 to 4 tonnes are the most utilised vehicle size by CEP service providers in last-mile deliveries due to weight limitations and other public authority road policies in a bid to tackle greenhouse gas (GHG) emissions in their cities.

The implementation of low-emission zones (LEZ) is one of the government policy measures which impose restrictions on specific vehicle types. In cities like Berlin, Munich, Aachen, Cologne, Eschweiler, etc., with low-emission zones, only allowed vehicle types are expected to go into this region, and the emissions stickers can identify the vehicle’s status with regards to accessibility into this region. According to the national scheme, the emissions sticker serves as proof of the vehicle’s emission standard and defaulting vehicles entering the low-emission zones are charged. All notable CEP service providers still have some light-diesel vans and trucks in their fleets, although the campaign to replace them with more sustainable means is being advocated.

Public authorities in European cities are expected to comply with EU Directive 2008/50/EC, which requires cities to eliminate adverse externalities (CO_2, NOx, PM, etc.) brought on by the transportation industry. This externalities concern has led to the consideration by some governments, e.g., England, France and Germany, to ban diesel vehicles from the inner-city region and support the shift to other sustainable alternatives. As a result, CEP service providers have to consider other sustainable transport vehicles for last-mile delivery, which might help reduce greenhouse gas (GHG) emissions (Rudolph et al., 2018).

2.3.2. Electric Trucks

The use of electric vehicles is a measure that has been advocated in recent years due to its low negative impacts on the environment (zero CO_2 emissions) and helps tackle diesel vehicle accessibility restrictions in low-emission zones. Electric vehicles are automobiles that use electricity instead of diesel to power the engine, i.e., there is a change of fuel type. Therefore, electric vehicles are considered viable alternatives to conventional vehicles for passenger and freight transport. However, they are more expensive to acquire, making conventional vehicles still more preferred by medium to small logistics firms for CEP services. Thus, logistics service providers often require some impetus, such as promoting their brand, government grant, tax relief, etc., to adopt electric vehicles into their fleets (Kleiner et al., 2017; Mehmedi, 2021).

Electric trucks are environmentally friendly trucks with the potential to help reduce the emissions generated by road transportation. Therefore, they will help logistics service providers meet the greenhouse gas (GHG) emissions targets. Although, the penetration of electric vans and trucks for freight transportation has been much slower than that of passenger transport due to vehicle limitations, governmental prioritisation, etc. (Kleiner et al. 2017). Nonetheless, the major providers of logistics services, such as DHL, Amazon, UPS, DPD and Hermes, have various fleets of vehicles, including at least one type of electric van/truck. Electric vans and trucks are being utilised in the freight industry for the different stages of freight activities, whether long-haul trunking, urban goods distribution, or on last-mile delivery operations to the customers. For example, battery electric vans are mostly used to deliver packages within urban areas due to their reliability and usefulness (Kleiner et al., 2017; Jones et al., 2020).

Electric vans and trucks are not practicable in all freight operations and situations due to their battery capacity limitation and the distance-based emission factor, as well as limited mileage, and inadequate public charging infrastructure, among others (Juan et al., 2016; Nicolaides et al., 2017; Bac & Erdem, 2021). There are also concerns regarding the electricity production sources as the production plants are not emission-free. The well-to-wheel analysis is used to assess electric vehicles to provide a more detailed analysis of overall emissions, i.e., emissions from driving the vehicle and emissions from the production plants generating the energy to be utilised to power the electric van/truck (Guandalini & Campanari, 2018). Renewable energy sources are recommended to maximise the emission-free benefit of electric vehicles (Juan et al., 2016; Guandalini & Campanari, 2018; Inkinen & Hämäläinen, 2020).

Various fuel types have been researched and implemented to generate the electricity required to power electric vehicles, giving rise to the variety of electric vehicles in the market today. The various types of electric vehicles based on 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 (Lebeau et al., 2015; Jones, Genovese & Tob-Ogu, 2020). In general, the benefits of electric vans and trucks are higher energy efficiency, low noise emissions, low CO_2 emissions, and cheaper operating costs. However, there are also restrictions which include limited battery capacity, lack of sufficient charging infrastructure, and lengthy charging duration, etc. (Juan et al., 2016; Nicolaides et al., 2017; Bac & Erdem, 2021; Mehmedi, 2021). Nonetheless, CEP service providers have increasingly integrated electric vans and trucks into their fleets of vehicles.

According to the DHL 2019 sustainability report, 15% of all post and parcel deliveries in 2019 by DHL in Germany were performed using electric vans and electric trucks, given their zero-emission delivery goal (Deutsche Post DHL Group, 2020). Furthermore, the Deutsche Post DHL Group has a target of 60% electric vehicles by the year 2030 for pickup and delivery services. DHL Group also owns an electric vehicle manufacturing company known as StreetScooter GmbH, which has manufactured some variants of electric trucks, such as WORK, WORK L and WORK XL, suitable for CEP services. Similarly, other logistics service providers such as Hermes, GLS, FedEx, DPD, UPS, Swiss Post, Amazon, etc. have electric vans and electric trucks performing last-mile deliveries in cities in a bid to adhere to public authority regulations with regards to emissions, maintain operational efficiency and promote business brand.

A study on UPS stated that using electric vehicles (mostly battery electric trucks) in 2016 saved 20,015 litres of diesel and 52.84 tonnes of carbon dioxide (Stodick & Deckert, 2019). The availability of public charging stations is essential to support the adoption of electric trucks and their operational range. It also helps eliminate the cost of providing this facility by the logistics service providers themselves. Although, there is still an issue regarding the adequacy and capacity of the charging stations and factoring charging time into the routing algorithm.

2.3.3. Cargo Bikes

Cargo bikes are three-wheelers with compartments to hold the load for easy transportation. They are an upgrade to cargo bicycles in terms of compartment capacity. There are various models of cargo bikes in terms of shape, size and capacity depending on their use cases. Use cases include carrying personal packages, shopping, food deliveries, transporting children, etc. From CEP service providers' perspective, cargo bikes are utilised to deliver parcels within short distances from the local distribution centre, making short tours. Cargo bikes are also utilised in deliveries from post offices to private customers within the neighbourhood and in cities with narrow streets. In the logistics industry, they are more suitable for last-mile delivery and collection activities.

Cargo bikes are considered an environmentally friendly alternative mode of transport because there are little to no emissions from utilising them. They are appropriate for locations with small streets, high business activity and delivery density (Schröder et al., 2015; Stodick & Deckert, 2019; Narayanan & Antoniou, 2021). However, cargo bikes are very limited in capacity and operational range and require physical efforts from the rider to move. Electric cargo bikes (known as e-cargo bikes) were developed to retain the application of cargo bikes and reduce the physical effort needed to propel them. In addition, e-cargo bikes are easier to use and provide electric assistance to the rider. Nonetheless, cargo bikes and electric cargo bikes have almost the same features and factors influencing their usage.

According to Narayanan & Antoniou (2021), the prevalence of e-cargo bikes is influenced by operational (i.e., catchment area, goods type and delivery density), vehicular (i.e., electric range, purchase price and technology), infrastructural (i.e., cycling infrastructure, urban morphology, charging stations and overnight storage facilities), workforce (i.e., socio-demographics and car ownerships), organisational (i.e., business sector, soft benefits, technology and innovation, sustainability and managerial support), and policy aspects (i.e., monetary, information dissemination, parking policies, vehicle access restrictions and trial schemes).

E-cargo bikes can increase service level, revenue, employment and liveability in cities when engaged for suitable freight deliveries. In addition, they can reduce total transport costs, energy consumption and negative environmental impacts such as greenhouse gas emissions and traffic congestion (Rudolph et al., 2018; Narayanan & Antoniou, 2021). Moreover, they are quite cheaper to acquire than conventional trucks and electric vehicles. Still, they do not have a direct replacement ratio, i.e., a cargo bike does not completely replace a diesel/electric truck due to notable differences like payload and speed.

Gruber & Narayanan (2019) highlighted the factors that influence the travel time of cargo bikes and the significant variables that constitute these factors. The factors are *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 – temperature and precipitation)*. Travel time is an essential factor in delivery operations. Still, it is unclear whether cargo bikes can compete with conventional vans/trucks and electric vans/trucks regarding travel time because the travel time of cargo bikes depends on the overall context of the freight trip.

Several studies have assessed the operational viability of cargo bikes for last-mile delivery against vans and trucks in terms of total transport costs, travel time performance and environmental emissions (Melo & Baptista, 2017; Zhang et al., 2018; Gruber & Narayanan, 2019; Llorca & Moeckel, 2020). They highlighted various factors influencing the performance of cargo bikes and proffered that the maximum benefits of cargo bikes for last-mile delivery can be achieved through short-distance trips under certain conditions. For example, cargo bikes are more efficient in cities with dedicated cycling infrastructures or high connectivity. They hence do not have to share the road network with cars and trucks, while utilisation of commercial trucks will increase vehicle density on the road and may lead to traffic congestion (Narayanan & Antoniou, 2021). Therefore, the benefits of cargo bikes may grow when traffic conditions on the road are worse for cars and trucks.

According to Melo & Baptista (2017), using Porto (Portugal) as the study area, e-cargo bikes can potentially substitute up to 10% of conventional commercial vans under certain conditions. They can also significantly reduce CO_2 emissions (e.g., up to 73%). Furthermore, they mentioned that the substitution could be as high as 10%, provided it is done in a suitable spatial context. Zhang et al. (2018) assessed the utilisation of cargo bikes for urban parcel delivery using a simulation-based approach for the city of Berlin, Germany, and they concluded that cargo bikes could reduce transport costs and emissions by 28% and 22%, respectively.

Generally, cargo bikes are still promising, taking into account the reduction in emissions associated with transportation. Cargo bikes have equally been observed to improve the traffic conditions of the network within which they have been implemented (Stodick & Deckert, 2019; Llorca & Moeckel, 2020; Narayanan & Antoniou, 2021). They are increasingly being utilised (especially e-cargo bikes) because of better energy efficiency, reduced emissions and less interference with road traffic. However, public authorities' interventions are required to propel the adoption of cargo bikes, e.g., the provision of good cycling infrastructure. Two major obstacles to adopting cargo bikes are limited payload (i.e., load-carrying capacity) and mileage compared to conventional and electric vehicles.

Micro-depots

Cargo bikes have a limited range; hence, they require support to increase their scope of operation from the immediate surroundings of the local distribution centres. Therefore, micro-depots have been studied recently as a solution to support cargo bikes in last-mile delivery. They are a viable solution to lessen the limitations of cargo bikes as a sustainable alternative for last-mile delivery. Cargo bikes can start their last-mile delivery journey from micro-depots, a form of logistics hub strategically positioned across the network. There are three types of transhipment points where freight goods can be merged, and they are urban consolidation centre (UCC), micro-consolidation centre (MCC) and transit point (TP) (Hofmann et al., 2017; Narayanan & Antoniou, 2021). Depending on the scale of logistics operations, these different transhipment points can be explored.

A micro-depot as a transhipment point is close to the customers. It sometimes consolidates and mainly transfers parcels for freight urban goods distribution. For example, parcels delivered to a micro-depot by diesel- or electric trucks can be transferred by cargo bikes for the final delivery to private customers. A micro-depot is usually about the size of a 20ft standardised container. In freight modelling, micro-depots as transhipment points can be dynamically generated and optimised through a decision support system, which identifies the best locations within the network. Fikar et al. (2018) developed a decision support system by integrating agent-based simulations, dynamic vehicle routing methods, and Geographic Information System (GIS) data.

Hofmann et al. (2017) conducted a simulation-based evaluation using street maps via GIS tools for multimodal distribution plans using Grenoble city, 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, traffic congestion and CO_2 emissions and improving air quality. In addition, micro-depots can increase the operational effectiveness of cargo bikes and guarantee timely deliveries of logistics operations.

Stodick & Deckert (2019) studied sustainable parcel delivery in urban areas with micro-depot using United Parcel Service (UPS) CEP services in Germany as a case study. It was noted that UPS significantly reduced its distance travelled and diesel consumption in 2016 due to adopting the micro-depot measure. The change to cargo bikes and micro-depots enabled UPS to save about 30,000 litres of diesel within a year, decrease emissions by 120 tonnes of carbon dioxide and reduce the distance travelled. Although, they argued that utilising cargo bikes with micro-depots is appropriate for majorly densely inhabited regions and that the integration of multiple delivery concepts might be necessary for some cities for efficiency.

Llorca & Moeckel (2020) also studied cargo bikes for parcel deliveries using FOCA (Freight Orchestrator for Commodity flow Allocation) model and the MATSim extension - freight. They observed that using a high number of cargo bikes alongside micro-depots reduces the total distance travelled using Munich, Germany, as the study area. However, it was also noted that 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, changes in micro-depot density were identified to affect the number of tours of cargo bikes. For instance, a decrease in micro-depot density leads to a slight decrease in the number of tours of cargo bikes and a notable increase in total mileage. As a result, the average distance a cargo bike travels per package increases, increasing emissions.

Micro-depot implementation is feasible when there is a positive outcome regarding cargo bike utilisation, delivery time, trip distance and greenhouse gas (GHG) emissions. The outcome also depends on the storage capacity of the micro-depot, availability of cargo bikes, good scheduling strategy and implementation strategy (Hofmann et al., 2017; Fikar et al., 2018; Rudolph et al., 2018; Gruber & Narayanan, 2019). Cargo bikes must be sufficient to meet the freight demand for deliveries, or delivery time will increase. Incorporating transport logistics hubs (e.g., micro-depots) into freight transport models is vital for more accurate freight modelling, expanding the network and good knowledge of related impacts. But lack of sufficient data on freight parameters and features of logistics hub hinders the proper integration of micro-depots in transport models (Huber et al., 2015).

Additionally, the integration of transport logistics hubs within models depends on the model characteristics such as the scale of analysis, spatial resolution, time horizon, or level of aggregation. It also depends on qualitative attributes (hub integration details) and quantitative attributes (number and types of logistics hubs) (Huber et al., 2015; Apostolopoulos & Kasselouris, 2022). Very few micro-depots exist as this is still a studied and explored area. Hence, studies on micro-depot prospects are often based on potential locations such as post offices (Zhang et al., 2018) and idle urban space - parking spaces in front of shopping centres and supermarkets (Fikar et al., 2018).

2.3.4. Autonomous Vehicles

Autonomous vehicles are automobiles that can sense their surroundings and function without human intervention. They use various in-vehicle technologies and sensors, such as adaptive cruise control, active steering, anti-lock braking systems, GPS navigation technology, lasers, etc. An autonomous vehicle is capable of driving on autopilot from a location to a set destination. Autonomous vehicles include aerial drones, ground robots and other unmanned vehicles (cars, vans and trucks). The use of an autonomous vehicle for last-mile delivery service is still new and being researched.

Unmanned aerial vehicles, also known as aerial drones or simply drones, are the most explored autonomous vehicle for last-mile delivery due to their serviceability. Drones are unmanned aircraft that can fly from one place to another at low altitudes and do not require large take-off and landing facilities like airports for aeroplanes. Therefore, they are considered a viable option for last-mile delivery with a tendency to reduce GHG emissions since it has zero interference with ground traffic. In addition, it can improve service levels and reduce delivery time and transport costs (Aurambout et al., 2019; Benarbia & Kyamakya, 2021). Examples of applications of drones by CEP service providers for last-mile delivery are DHL Parcelcopter in Germany, Amazon Prime Air in California, UPS Workhorse in the United States and DPD drone delivery in Isère, France.

Drones have been implemented as a last-mile delivery concept in mainly two forms (Aurambout et al., 2019; Benarbia & Kyamakya, 2021). One is a direct delivery from the distribution centre to final customers, and the other is a mixed-delivery approach where drones and vans or trucks cooperatively perform the last-mile delivery to customers based on optimisation techniques. The distribution centre for the drone delivery concept is sometimes called a drone beehive based on its configuration. Drones have limited load capacity and limited range. Thus, they require charging stations to recharge their batteries or swap them to increase their mileage and maximise their potential for last-mile deliveries. In a mixed delivery concept, the van/truck rooftop can serve as the drones' landing and take-off station and the charging station (Feng et al., 2018; Benarbia & Kyamakya, 2021).

Ground robots are already being utilised for food delivery services, e.g., the application of Starship delivery robots for food delivery services in the United States (majorly within universities), the United Kingdom and Estonia (Wessling, 2022). FedEx, a CEP service provider, has also explored using ground robots (known as Roxo) for last-mile delivery but announced to shut down the service in October 2022 (Contreras, 2022). Amazon.com Inc. also announced the scale-down of its research on robotic last-mile delivery (Amazon Scout) in the same month. These ground robots are autonomous and built to use the pedestrian walkway at low speed. In addition, other autonomous vehicles such as autonomous cars, vans, buses and trucks are being researched and tested to assess their suitability for commercial operation and their effect on the existing traffic condition and the environment. Generally, the prospects of autonomous vehicles for last-mile delivery are still being researched and tested.

2.3.5. Parcel Shops and Parcel Lockers

Parcel shops, also known as post offices, are retail stores that offer postal services to private customers on behalf of a CEP service provider. That is, owners of retail stores partner with a CEP service provider to render parcel pickup, collection and dispatch services to private customers. In addition, they usually render another service alongside the postal services within the same place, with one being their primary business and the other as a supplement. Parcel shops also sell packaging folders/envelopes, postage stamps and stationaries. All major CEP service providers are exploring the post office concept to expand their network and catchment area.

Parcel lockers, also known as hub lockers, are automated booths that offer self-services to customers with respect to the collection, pick up and dispatch of parcels without a time limit (Sułkowski et al., 2022). They are a secure and contactless delivery system that is only accessible to the parcel recipient. Parcel lockers are ideal for large parcels that cannot fit household mailboxes and postal services outside regular working hours. In Germany, there are mainly DHL packstations and Amazon hub lockers which are numerous in various neighbourhoods across cities. They allow private customers to pick up parcels and drop parcels for shipping.

Private customers are required to cover some walkable distance in parcel shops and parcel lockers concepts to access their services. But it gives private customers a longer time window to pick up their parcel at their convenience compared to home delivery, which takes only a few minutes to become a failed delivery. According to Deutsche Post DHL Group (2022), parcel lockers can store parcels for seven days, including the delivery day. Parcel lockers are usually strategically located within walkable distances in neighbourhoods based on economic activity and the number of inhabitants. Therefore, they save time, help eliminate failed home deliveries and can reduce total transport costs. According to Sułkowski et al. (2022) study, which analysed the effects of the COVID-19 pandemic on last-mile logistics innovations using the Polish CEP market, the use of parcel lockers is identified as a viable last-mile delivery solution for now and the future. Although, there is a need to increase the parcel locker's capacity and information technology integration.

2.3.6. Crowdsourcing

Crowdsourcing of last-mile delivery is an approach to achieve parcel delivery by engaging the service of local couriers or private individuals to transport parcels to the final recipients. CEP service providers, like logistics providers in general, sometimes outsource some of their delivery services to third-party logistics providers to concentrate on their primary freight operations. The crowdsourcing delivery concept is complex, with various operation modes depending on the employed delivery system of the third party engaged. CEP service providers adopt crowdsourcing when they need to fulfil deliveries outside their catchment areas or have high seasonal demands (Mladenow et al., 2015; Zhen et al., 2021). Depending on the agreement, the outsourced last-mile delivery may be carried out by individuals looking to earn extra money, e.g., Amazon Flex program or established third-party logistics operators (DispatchTrack, 2020). The third-party logistics operator can perform this task using a conventional vehicle or an electric vehicle – e-cargo bikes, electric vans/trucks or drones.

Crowdsourced delivery is more flexible and requires less capital investment than other delivery methods (Mladenow et al., 2015). Therefore, it is important to consider it as a feasible delivery concept to tackle growing freight demand. Crowdsourcing can be explored when the customers are not within the CEP service provider's network, and rendering the delivery service will be more costly. Outsourcing this type of delivery even to a competitor might be more cost-effective (Zhen et al., 2021). A notable example of crowdsourcing is the Amazon Flex program, where individuals partner with Amazon.com Inc. to help fulfil their freight delivery demand using their cars. The individuals go to an assigned Amazon distribution centre to pick up the parcels to be delivered. This concept also helps the individuals earn extra money, and they can choose tours that suit their schedule and when to work.

Crowdsourced last-mile delivery can start from the primary service provider’s depot or a micro-consolidation centre. The work of Zhen et al. (2021) proposed six different modes of operation for crowdsourced delivery and used mathematical models to evaluate them quantitatively. Crowdsourcing can potentially reduce the negative externalities associated with CEP services, but it is not easy to assess the concept collectively. Furthermore, the possibilities of crowdsourcing are quite dynamic, and its benefits and prospects depend on use cases. Hence, it would not be considered further in this research.

3. Methodology

A literature review-based analysis was conducted to identify the existing logistics measures of courier, express and parcel (CEP) service providers. First, the literature search was conducted using keywords such as CEP (courier, express and parcel), CEP service providers, freight delivery concepts, last-mile delivery, logistics measures, parcel delivery, urban goods distributions, and urban logistics. Then, an empirical analysis was performed using the agent-based transport simulation MATSim (Axhausen et al., 2016) and the integrated logistics behaviour model jsprit (Schröder et al., 2012).

3.1. Multi-Agent Transport Simulation (MATSim)

MATSim is an acronym for Multi-Agent Transport Simulation. MATSim is an agent-based modelling software where each agent interacts with its environment and tries to maximise its utility. This modelling software helps to evaluate different transport-related problems at a mesoscopic level and assess the potential solutions before the actual implementation of the solutions. It also helps in transport planning and decision-making. Prerequisites for running MATSim include installing MATSim, the Java Development Kit, and a Java IDE (such as IntelliJ or Eclipse). All the processes involved in the execution of MATSim projects can be explained using the MATSim cycle (also known as MATSim loop).

The MATSim cycle describes the steps involved in the execution of a MATSim project. It includes the initial demand, mobsim, scoring, replanning, and analyses, as shown in Figure 3.1 (Axhausen et al., 2016).

- **Initial Demand:** This refers to at least the population file (i.e., agents and their plans), network file and config file, among others required to initialise the simulation model. The config file contains the settings that control the simulation. For example, it defines how the simulation acts regarding strategies, number of iterations, input files, etc. The population file contains all the agents in the study area and their initial plans, i.e., activity chains. The network file refers to the transportation infrastructure on which the agents' plans are to be performed and assessed. The network file consists of nodes and links. Each link is associated with an origin node and a destination node and has other attributes such as length, capacity, free speed, modes, etc.

  The network and population files must have the same coordinate reference system (CRS) for the simulation to generate accurate and reliable results. The same applies to other input files with location details. Additional files would be required depending on the application area. For instance, modelling schedule-based public transportation would require additional files like the public transport schedule, type of vehicles and their specifications.

- **Mobsim:** Mobsim refers to mobility simulation, and it is the next step after the agents have each selected a plan. It is the actual simulation along the network, after which the agents score themselves based on their plan's performance. The two implementation methods of mobsim in MATSim are QSim (Queue-Simulation) and JDEQSim (Java Discrete Event Queue Simulation). QSim is the default method and uses a time-step-based approach. The queue model represents links as queues with vehicles in a particular order, usually FIFO (first-in, first-out). While in JDEQSim, the waiting queue is combined with an event-based update step, i.e., teleportation.

- **Scoring:** This refers to the reward value associated with the execution of a plan of an agent using a utility function. After each iteration, all agents score their executed plans, which could be positive or negative based on the set of activities done. For instance, time spent at activities like work and home increases the score, while time spent travelling decreases it. If the travel time could be reduced, agents can then gain utility from additional time for activities while avoiding negative travel marginal utility. Agents change their scores by changing their plans to be executed in the next iteration to maximise their scores.

  The coevolutionary algorithm used by MATSim ensures that all agents within a system are interacting in the best possible way based on their daily plans and prevents any single agent from maximising its score at the deprivation of another. The process eventually results in a stochastic user equilibrium, where a system optimum is created using a global fitness function that ensures optimisation within the collection of agent plans.

- **Replanning:** In MATSim, agents are capable of learning from their previous experiences and environment. Hence in an attempt to perform better than the previous iteration step, agents can choose a different strategy depending on the available option in the model being executed (e.g., innovative strategies such as mode choice, route choice, departure time choice, etc.) available to the agent. That is, the initial plans of each agent are updated after each iteration as each agent tries to maximise its utility. In the long run, this allows for an optimum state such that each agent chooses the best plan possible.

- **Analyses:** Analyses are carried out after the simulation's completion to assess the simulation results. After the completion of the simulation, there is an output folder containing the results of all predefined analyses and events alongside an output network file, events file, plans file, config file, etc. Some of these files, like the output network file, events file and plans file, can be utilised for further analysis and visualisation. The output plans file is not a duplicate of the input plans file but the updated plans file. This is because some agents would have changed their plans from the initial plans during the simulation to maximise their scores. The output events file is very important because it contains the step-by-step activities of all agents during the simulation run. In addition, the log file contains all the details of the simulation - running records and processing information.

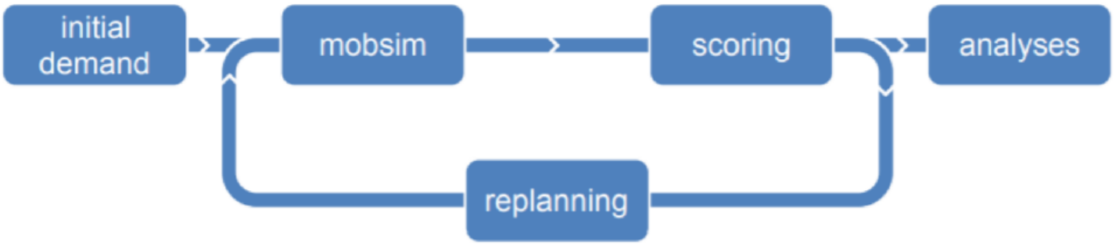


Figure 3.1 MATSim Cycle

Note: Adapted from the work of Axhausen et al. (2016)

MATSim simulations can be run either through the GUI (Graphical User Interface) function or by code. The GUI allows for the visualisation of the simulation while it is running but requires higher computation power and takes a longer time to complete the simulation. On the other hand, running MATSim by code enables simulations to run faster and with lesser computational requirements, but there is no visualisation of the simulation while it is running. The basic functionality of MATSim is for agent-based modelling with a focus on activity chains. However, several extensions that enhance the functionality of MATSim have been developed, such as the freight extension. They can be explored depending on the application area.

3.2. Jsprit Freight Module

For freight modelling, Schroeder et al. (2012) proposed a multi-agent freight transport model where logistical choices are divided into two different roles. These roles are carriers who design routes and schedule vehicles, and transport service providers who build transport chains. Both agent types can integrate and achieve economies of scale at their respective levels. Jsprit is an open-source tool built on the Java programming language. It offers computational strategies for resolving the travelling salesman problem and vehicle routing problem (Schröder et al., 2012; Graphhopper, 2022). Jsprit can be integrated into MATSim using a freight plugin to simulate the logistics choices made by logistics service providers. The functionalities of jsprit include solving vehicle routing problems with pickups and deliveries, with various fleets, from numerous depots, at different time windows, etc. Jsprit is recognised as a route optimisation tool and offers the possibility to choose a daily plan, set the vehicle type of vehicle, assign the distribution centre from which a consumer is supplied, the order of the customers to be served per route, and time of departure from the distribution centres.

For transport research, the behaviour of logistics service providers and their logistics measures have been modelled using a combination of MATSim and jsprit. There are several examples of this application. Schröder et al. (2015) analysed smart policy options for urban CEP transport using MATSim and jsprit. Thaller (2018) 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 traffic. Zhang et al. (2018) assessed the utilisation of cargo bikes and parcel pickup points in urban parcel delivery using MATSim with jsprit. Adeniran (2020) 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 research.

3.3. Modelling Procedure

The modelling procedure of the combined application of MATSim and jsprit for freight transport modelling is shown in Figure 3.2. The modelling procedure has three stages. Demand preparation is the first stage, where input data are loaded and ready to initialise the simulation world. All input files needed for a case study must be provided with respect to the study area and connected to the project to run successfully. The main input files required for freight transport modelling are network file, vehicle type and specifications, fleet size, transhipment locations, private customers (based on population and share of e-commerce users), commercial customers and CEP service providers, i.e., their distribution centres, post offices, parcel shops and parcel lockers.

Others include the configuration input files, variables and the freight demand for private and commercial customers. All these are used to initialise the simulation world. It is noteworthy to mention that all location information must be in one coordinate reference system appropriate for the study area. There should be location coordinates for each entry in the private customers, commercial customers, transhipment locations, distribution centres, post offices, parcel shops and parcel lockers files. Once the simulation is initiated to run, it reads all these input files and variables. The simulation world then builds the vehicle type to be utilised based on vehicle features information and generates customers' requests. Each customer's 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 for delivery.

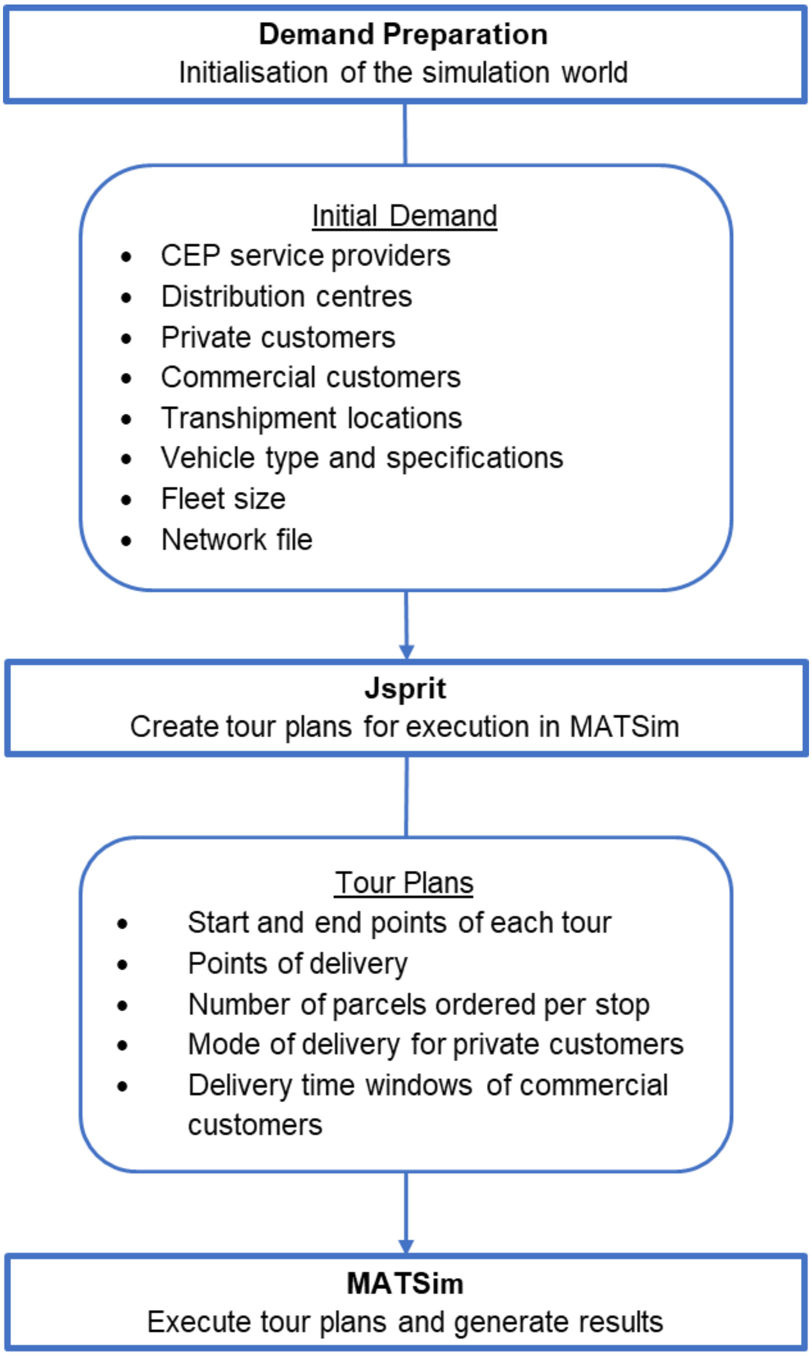


Figure 3.2 Modelling Procedure of the Research

Note: The modelling procedure was adapted from Adeniran (2020), which is based on the work of Thaller (2018)

In the second stage, jsprit creates tour plans to be executed in the MATSim based on the received customers' requests. Then, jsprit computes solutions to the vehicle routing problem, which captures the tour plans. In its computation, jsprit requires the number of shipments, operating time windows, the number of vehicles and their features, and the mode 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, mode of delivery for private customers, and delivery time windows for commercial customers. In the third stage, the created tour plans from jsprit are executed using MATSim, and they are analysed based on predefined event handlers to generate more meaningful results. Passenger traffic can be simulated alongside freight traffic using MATSim and jsprit to evaluate the entire transport system of the study area.

4. Case Study

A geographical region is classified as a city depending on its population (i.e., number of inhabitants), importance to the surrounding region, land mass and road network. The most utilised factor for classification is the population; however, there is no generally accepted range for city classification using the population, even in Europe. Since this research focuses on the courier, express and parcel (CEP) services and the Federal Republic of Germany is a major actor globally, the classification according to the Federal Office for Building and Regional Planning (Bundesamt für Bauwesen und Raumordnung) as defined for Germany was adopted.

According to the Federal Office for Building and Regional Planning, a municipality inside a municipality association or the united municipality itself is referred to as a "city" if it has at least 5,000 residents or a fundamental central role. On the other hand, the association of municipalities or the unitary municipality is a rural municipality if none of these characteristics applies to them (Bundesamt für Bauwesen und Raumordnung, 2020). Further classification of a city is as follows:

- **Large city:** A large city is a municipality of a municipal association or unitary municipality with at least 100,000 inhabitants. It usually has at least one central function. Large cities can be divided into 15 large cities with at least 500,000 inhabitants and smaller large cities with less than 500,000 inhabitants.
- **Medium-sized city:** A medium-sized city is a municipality of a municipal association or unitary municipality with at least 20,000 to 99,999 inhabitants. It primarily has a medium-central function. Medium-sized towns can be divided into large-medium-sized towns with at least 50,000 inhabitants in the municipality of a municipal association or unitary municipality and small-medium-sized towns with less than 50,000 inhabitants.
- **Small-sized city:** This is a municipality of a municipal association or unitary municipality with at least 5,000 to 19,999 inhabitants or has at least a basic central function. The group of small towns can be divided into larger-small towns with at least 10,000 inhabitants in the municipality of a municipal association or unitary municipality, small-small towns with less than 10,000 inhabitants.

In view of the above classification, the Aachen city region (Städteregion Aachen) in the Federal Republic of Germany was selected as the study area for this research because of its municipality structure which contains more than one of the intended city types to be studied as shown in Figure 4.1. The Aachen city region (Städteregion Aachen) is located southwest of North Rhine-Westphalia, Germany. It is located at the border triangle with the Netherlands and Belgium. The Aachen city region was established as the legal successor to the district of Aachen on October 21, 2009. It consists of the independent city of Aachen and seven other cities (StaedteRegion Aachen, 2020; Statistische Ämter des Bundes und der Länder, 2020; Statistikportal, 2021). The Aachen city region 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.

The independent city of Aachen is the most populated with 248,878 inhabitants. Roetgen – a small-medium-sized city - is the least populated with 8,650 inhabitants according to 2020 population data from the Federal and State Statistical Offices (Statistische Ämter des Bundes und der Länder, 2020). The city of Aachen has a long history of planning for environmentally friendly urban mobility. It was designated as a German model region for mobility management between 2009 – 2011 and electromobility since 2010 by the German Federal Ministry of Transport (CIVITAS, 2020).

Table 4.1 Statistics on Municipalities within the Aachen City Region

Municipalities	**Population**		**Population Density**	**Surface (km^2)**
	2019	**2020**	**2020**	
Aachen City	248,960	248,878	1,548.80	160.69
Alsdorf	47,149	47,330	1,493.60	31.69
Baesweiler	27,093	27,319	994.60	27.47
Eschweiler	56,482	56,172	739.40	75.97
Herzogenrath	46,375	46,225	1,388.40	33.29
Monschau	11,693	11,686	124.10	94.19
Roetgen	8,648	8,650	219.40	39.43
Simmerath	15,404	15,498	139.60	111.05
Stolberg	56,466	56,377	571.90	98.57
Würselen	38,756	38,496	1,117.00	34.46
Städteregion Aachen	**557,026**	**556,631**	**787.50**	**706.80**

Note: Data are extracted from the website of Statistische Ämter des Bundes und der Länder (2020)

Characteristics of the Aachen city region are as follows:

- State: North Rhine-Westphalia
- Population: 556,631 (2020)
- Area: 706.8 km^2
- Population Density: 787.5 per km^2

- GDP: 21,127 million EUR (2020)
- Administrative district: Cologne

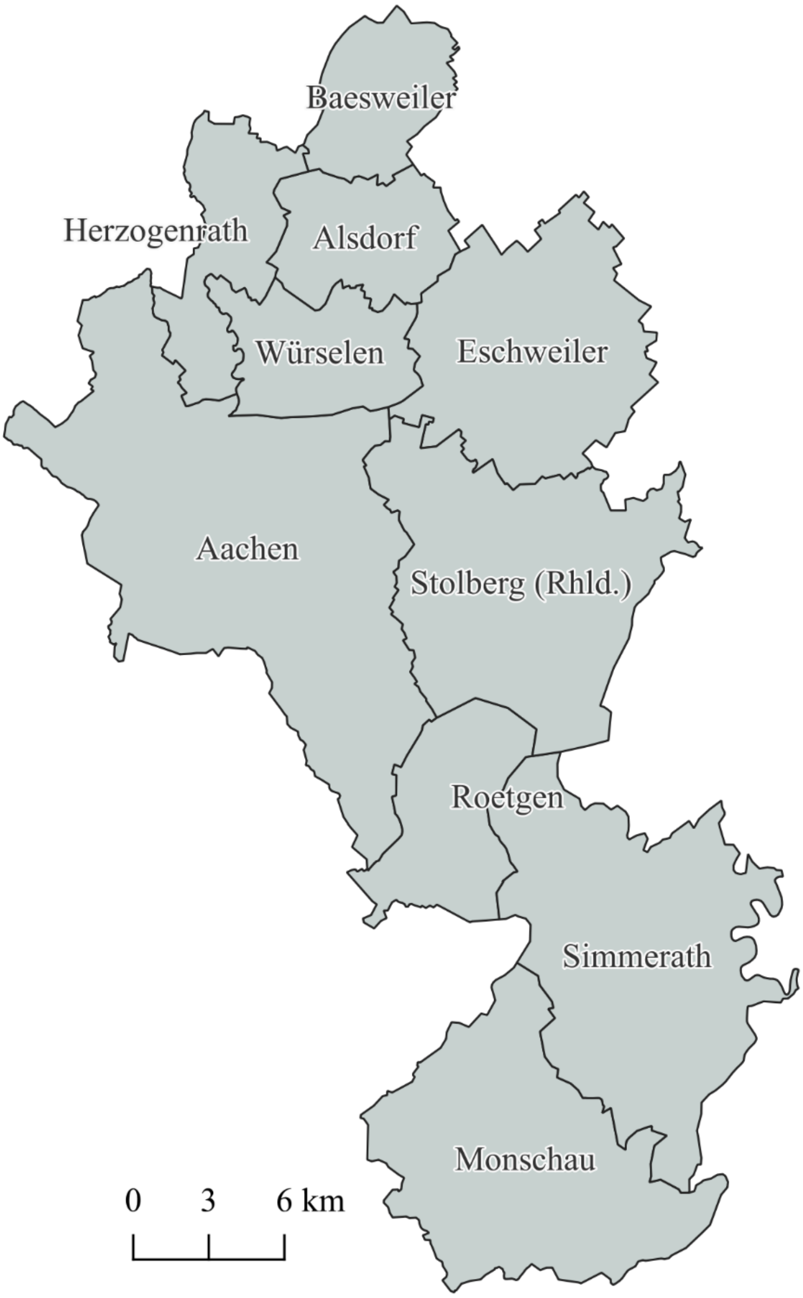


Figure 4.1 Aachen city region (Städteregion Aachen)

4.1. Data Collection and Preparation

Data preparation is an essential step towards the modelling of the scenarios. It involves gathering relevant data that are useful in building the synthetic state in the simulation and the scenarios to be analysed. Most of the data utilised in this research are secondary data. MATSim requires the network file, configuration file, population file and others such as vehicle types, etc. The network is the road network infrastructure connecting the regions, and the population file contains the actors modelled and their respective location details. Based on their relevance, the actors utilised in this research are private customers, commercial customers, micro-depots and CEP (courier, express and parcel) service providers with their distribution centres, parcel shops, post offices and parcel lockers. All coordinate information is obtained in or converted into the Gauß-Krüger-Zone 4 coordinate system (also known as GK Zone 4 or EPSG: 31468) because it is one of the appropriate coordinate reference systems for the geographical region of Germany. Also, 2020 is the reference year for analysis due to the lack of relevant data for 2021. Table 4.2 summarises all input data, their characteristics, and sources used in the simulation.

Table 4.2 Overview of Data Collection

Input Data Used	**Characteristics**	**Sources**
Private Customers	The synthetic population of the study area and share of e-commerce users	Institute of Transport Research, DLR and VuMA (2021)
Commercial Customers	Potential businesses in the study area based on location type, as defined by Thaller (2018), with a tendency to use CEP services	OpenStreetMap database
Freight Demand	B2B and B2C freight demand per day in the study area	Estimated using the freight demand development module from Thaller (2018)
CEP Service Providers' Distribution Centres	Existing distribution centres serving the study area	Websites of CEP service providers - DHL, DPD, GLS, Hermes and UPS
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	Existing parcel lockers - DHL Packstation and Amazon lockers - in the study area	DHL and Amazon websites
Micro-depots	Potential micro-depot locations in the study area	OpenStreetMap database
Road Network	Road network of the study area	OpenStreetMap database
Freight Vehicles	Type and technical specifications of vehicles to be used in the simulation world	ADAC (2022) and BIEK (2017)
Emission Conversion Factors	Fuel based conversion factor of CO_2, CO, PM_{10}, HC and NO_X	Thaller (2018) and Icha et al. (2022)

4.1.1. Private Customers

Private customers refer to individuals within the study area that are potential customers for parcel delivery on a typical day. They are based on synthetic population data of the Aachen city region. The data was obtained as secondary data from the Institute of Transport Research, Deutsches Zentrum für Luft- und Raumfahrt. The synthetic population data contains 533,349 persons in the Aachen city region with their age groups and geographical coordinates. The age distribution was categorised into nine groups, which are 0–9, 10–19, 20–29, 30–39, 40–49, 50–59, 60–69, 70–79, and ≥80. Not every person within the region uses courier, express and parcel services; hence it is important to ascertain what shares of the inhabitants use CEP services and integrate this into the simulation. The share of online shoppers in Germany in 2020 by age group, according to VuMA (2021), is as shown in Table 4.3, which was based on a survey with 7,963 respondents and was projected to 25.16 million people. It presents the share of persons that did at least one online shopping in 2020 in Germany using age group categorisation.

Table 4.3 Share of Online Shoppers in Germany in 2020 by Age

Age Group	2020
14 – 19	7.4%
20 – 29	18.5%
30 – 39	20.7%
40 – 49	17.1%
50 – 59	18.9%
60 – 69	11.5%
70 -	5.9%

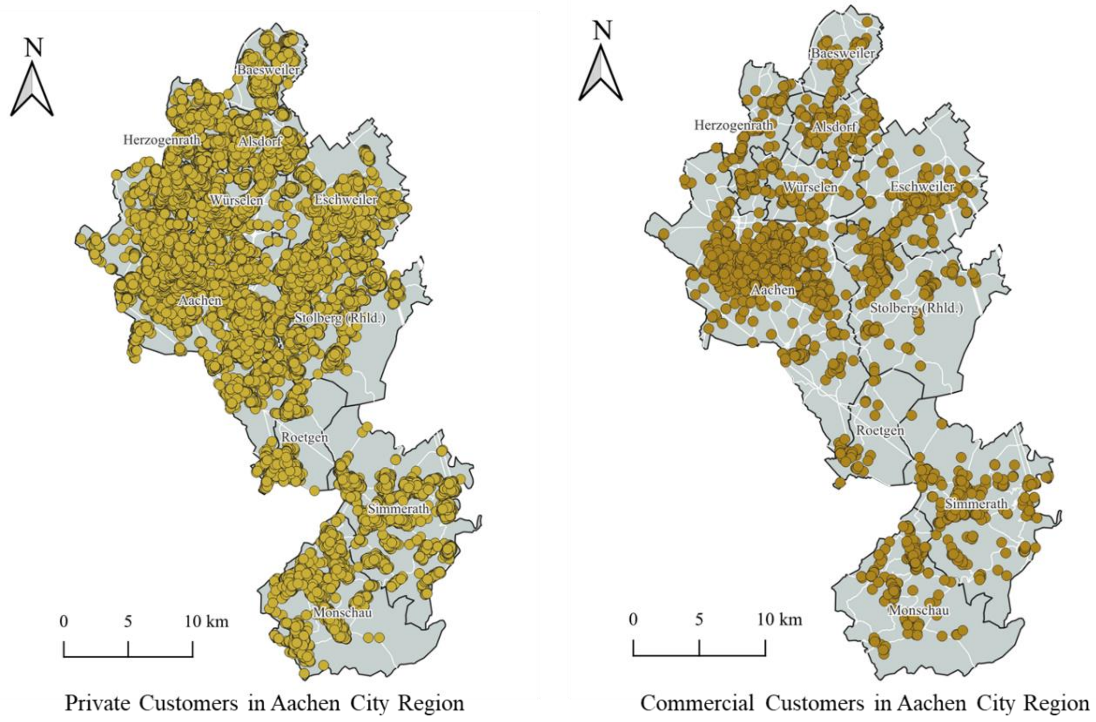
Note: Data adapted from the report of VuMA (2021) on the share of online shoppers in Germany

The report does not contain information on persons before the age of 14 years; in most cases, an older person in their household usually places their online orders. Thus, it is assumed to be zero per cent. Table 4.3 shows that persons from the age of 14 to 19 have a share of 7.4%, aged 20 to 29 with 18.5%, aged 30 to 39 with 20.7%, aged 40 to 49 with 17.1%, aged 50 to 59 with 18.9%, aged 60 to 69 with 11.5%, and aged 70 and above with 5.9%. People between the age of 20 to 59 are more active in online shopping than others. Furthermore, the share of private customers utilising CEP services is derived by integrating the share of online shoppers using the age distribution of the synthetic population of the Aachen city region. Table 4.4 shows the share and number of private customers of CEP services in the Aachen city region, which are inputs for the simulation. It is assumed that freight delivery requests are limited to one per private person.

Table 4.4 Features of the Synthetic Population of the Aachen City Region

Age Group	Number of Persons	Share of Online Shoppers	CEP Private Customers
0 – 9	51,827	0%	0
10 – 19	58,946	7.4%	4,362
20 – 29	78,948	18.5%	14,605
30 – 39	62,106	20.7%	12,856
40 – 49	78,449	17.1%	13,415
50 – 59	73,304	18.9%	13,854
60 – 69	55,931	11.5%	6,432
70 -	73,838	5.9%	4,356

Note: Synthetic population of the Aachen city region was obtained from the Institute of Transport Research, DLR



Private Customers in Aachen City Region

Commercial Customers in Aachen City Region

Figure 4.2 Private Customers and Commercial Customers in the Aachen city region

4.1.2. Commercial Customers

Commercial customers refer to businesses that require the services of CEP service providers. They are responsible for the volume of B2B (Business-to-Business) freight trips. Unfortunately, there is no available information on all existing commercial customers of CEP services within the study area. Therefore, potential commercial customer data was extracted from the OpenStreetMap database using land-use type (e.g., industry, retail business, leisure, shopping, etc.). The application of land-use types to identify potential commercial customers, as shown in Table 4.5, was adapted from the work of Thaller (2018), which was designed following the German classification of economic activities (2008). This approach identifies 3,812 potential commercial customers within the Aachen city region. The time window for B2B deliveries is 09:00 to 18:00, which is the average working hours of most businesses.

Table 4.5 Location Types of Commercial Customers

Land-use Types	Number	Potential Commercial Customers
Access points, Shopping facilities	88	Petrol stations
Educational facilities, Workplaces	229	Research institutes, University
Leisure facilities	1019	Gastronomy, Hospitality / Catering
Leisure facilities, Workplaces	29	Beauty / Cosmetic care, Hairdresser, Solarium, Tailor
Shopping facilities	917	Bookshop, Clothing, Computer shop, Department stores, Electronic market, Fabric Shop/ Textile, Gift shop, Higher-level retail, Jewellery, Kiosk, Mobile phone shop, Newsagent, Optician, Outdoor shop, Pharmacies, Shoe shop, Shopping centre, Sports shop, Stationery shop, Toy shop, Video shop, Watch shop and Other shops.
Workplaces	1530	Administration, Bank, Business office, Commercial offices, Library, Police, Politics, Public building, Travel agency, Unspecified business

Note: Adapted from the work of Thaller (2018)

4.1.3. Freight Demand Development

The freight demand per day for business-to-business (B2B) and business-to-consumer (B2C) are estimated using the freight demand development module developed by Thaller (2018). The freight demand development module uses system dynamics to estimate freight demand per day based on the interdependencies between freight customers and freight demand. It takes into consideration the relationships between these variables – population, gross domestic product (GDP), the total volume of CEP shipments, and CEP index of B2B and B2C – with regards to the study area and their changes over time, e.g., ten years in the system modelling. For 2020, the freight demand for private customers on a typical day in the study area was estimated as 42,801 parcels, which are to be randomly distributed among the prospective private customers. And the freight demand estimation for commercial customers on a typical day was 41,907 parcels, which are to be randomly distributed among the potential commercial customers.

4.1.4. CEP Service Providers

CEP service providers are logistics operators providing courier, express and parcel services to private persons and businesses. They play an important role in urban goods distribution, enhancing cities' economic development. Only the major CEP service providers in Germany are considered in this research because they collectively moved

93% of the freight volume in Germany in 2020 (Pitney Bowes, 2022). The CEP service providers considered in this research are Deutsche Post DHL, Hermes Group, DPD Group, United Parcel Service (UPS) and General Logistics Systems (GLS). The information about their distribution centres, post offices, parcel shops and parcel lockers are extracted from their respective websites and reports.

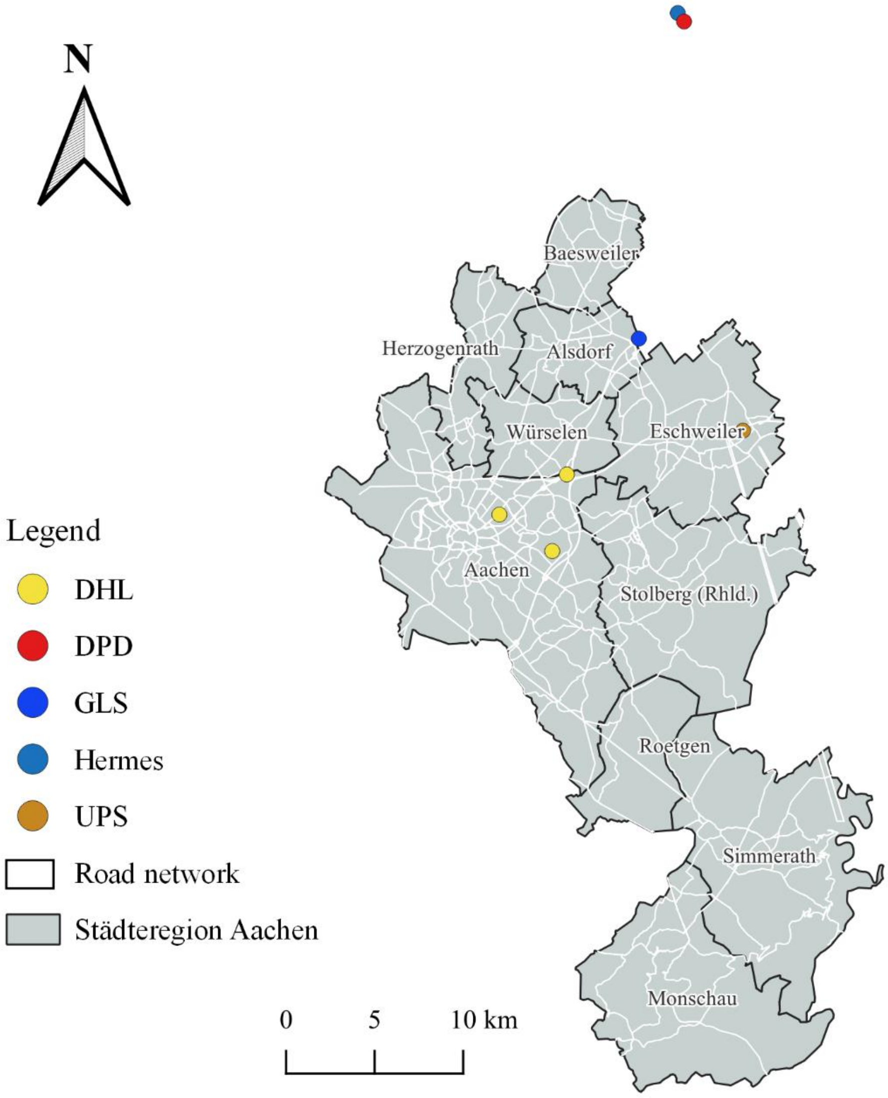


Figure 4.3 Distribution Centres in the Aachen City Region

Nine (9) distribution centres of these CEP service providers are identified. However, some are not located within the study area but are located in cities close to the study area and serve as distribution centres for the study area. Their location coordinates have also been converted into the GK Zone 4 coordinate system. The delivery tours for the last-mile originate from these distribution centres. This research did not evaluate logistics measures based on the different CEP service providers. Rather, they are considered as one entity (i.e., white label), and all the distribution centres belong to this entity. In addition, 377 parcel shops (including post offices) and 82 parcel lockers are identified within the Aachen city region.

Similar to commercial customers, micro-depots are extracted based on potential micro-depot locations from the OpenStreetMap database using land-use type. The potential micro-depot locations are free urban spaces such as parking areas in front of gas stations, supermarkets and shopping centres, as defined by Fikar et al. (2018). This is because these areas are usually surrounded by large open spaces and are only used momentarily. As a result, 223 potential micro-depots are identified for the Aachen city region.

4.1.5. Road Network

The road network refers to the road infrastructure that connects the entire region. It is made of links and nodes. The nodes serve as points where two or more links meet. Each link starts at one node and ends at another, and this also depicts the direction of travel. Each link has attributes such as length, capacity, free speed, mode, and the number of lanes. It is better to consider the surrounding traffic on the road network when modelling freight transportation because there are not only freight vehicles on the road, i.e., modelling of the freight traffic concurrently with passenger traffic.

To incorporate the surrounding traffic into the model, it is best practice to use a calibrated road network of the study region because the calibrated road network is close to the real state of the study region. However, there is no calibrated road network for the Aachen city region to the best of my knowledge at the time of writing this report. And preparing a calibrated network would take considerable time, which may affect the main focus of this research. Hence, the free speed of certain links is modified to account for surrounding traffic effects. The road network of the study area was extracted from the OpenStreetMap database, and it was converted, simplified and georeferenced to Gauß-Krüger-Zone 4 coordinate system using Java. The free speed on specific link types in the prepared road network is modified to account for surrounding traffic effects. The method considered in this research is the use of the congestion rate of the study area.

The average congestion level for the Aachen city region was obtained from the TomTom traffic index report (TomTom, 2022). The traffic report states that the average congestion level in the study area was 26% in 2020, i.e., travel time during congestion is 26% longer than movement at a free-flow state within the network. For instance, there will be additional 13 minutes of travel time for a typical fifty-minute trip during a congested state. There is a relationship between average speed, distance and travel time, as displayed in the equation below. Average speed and travel time are inversely proportional to one another, provided distance is kept constant, i.e., an increase in travel time will decrease the average speed. Thus, a 26% decrease in speed is applied to the link free speed.

$$Average\ speed = \frac{Distance}{time}$$

Therefore, the change in speed was implemented by accessing the link's length and free-speed values. It is noteworthy to mention that the change in speed was not applied to all road types (i.e., links) in the road network file but only on roads with principal tags – motorway, trunk, primary, secondary, tertiary, unclassified and residential – and their link roads – motorway-link, trunk-link, primary-link, secondary-link, tertiary-link – as defined by OpenStreetMap (2022). The link length is the distance, and the travel time for each considered link was calculated by dividing the length by free speed. The congestion rate was then applied to the travel time to obtain a new travel time in a congested traffic state, as shown in the equation below. The new speed per link is then calculated by dividing the link's length by the new travel time. All of these were done using Java. After that, the road network was ready as an input for the simulation initialisation. The road network contains 83,885 nodes and 195,567 links.

$$New\ travel\ time = \ travel\ time + (travel\ time\ \times congestion\ rate)$$

4.1.6. Freight Vehicles

It is essential to consider freight vehicles because they are the means of transport used to carry freight goods from distribution centres to customers. Hence, details about the vehicle fleet of CEP service providers are required to model the actions of these CEP service providers in the simulation. This research assumes that light-duty trucks (category N1) weighing 3.5 tonnes are the conventional vehicle for last-mile delivery and urban goods distribution. The required vehicle features are purchasing cost, tank size, fuel consumption, total permissible weight, payload, range and maximum speed, maintenance costs (e.g., tyres costs), depreciation and interest costs. In addition, they aid in calculating transport costs (including fixed, variable, and personnel costs).

For the simulation initialisation, the VW Commercial Vehicles Crafter 35 panel van (VW Nutzfahrzeuge Crafter 35 Kastenwagen) is used as the typical diesel truck utilised by CEP service providers. The electric truck utilised is the VW Commercial Vehicles e-Crafter panel van (VW Nutzfahrzeuge e-Crafter Kastenwagen). Some relevant vehicle features are highlighted in Table 4.6 and are gathered from ADAC (2022).

Table 4.6 Vehicle Features of Diesel and Electric Trucks

Vehicle Parameters	**VW Commercial Vehicles Crafter 35 panel van**	**VW Commercial Vehicles e-Crafter panel van**
Vehicle type	Light-duty truck	Light-duty truck
Fuel source	Diesel	Electric
Vehicle weight class	3.5 tonnes	3.5 tonnes
Payload (in kg)	1478 kg	998 kg
Permissible total weight (in kg)	3500 kg	3500 kg
Empty weight	2022 kg	2502 kg
Volume (in m3)	9.9m3	10.7 m3
Battery size (in litres)	75.0 l	35.8 kWh
Range (in km)	872 km	173 km
Energy consumption	0.086 l/km	0.296 kWh/km
Maximum speed (in km/h)	143 km/h	90 km/h

Note: Technical specifications of these vehicles are extracted from ADAC (2022).

Gruber & Narayanan (2019) identified five distinct e-cargo bikes used for delivery services based on the number of wheels and construction type. The e-cargo bikes are pizza delivery bikes, long john bikes, longtail bikes, front-load tricycles and heavy-load tricycles. The e-cargo bike used is the Musketier model, which is a heavy-load tricycle with moderate load capacity. Some relevant features are shown in Table 4.7.

Table 4.7 Vehicle Features of E-Cargo Bike

E-Cargo Bike Parameters	**Values**
Vehicle type	Cargo bike
E-bike type	Pedelec
Fuel source	Electric
Vehicle weight class	0.30 tonnes
Payload (in kg)	242 kg
Permissible total weight (in kg)	300 kg
Empty weight	58 kg
Volume (in m3)	1.33 m3
Battery size (in litres)	0.518 kWh
Range (in km)	46 km
Electricity consumption (kWh/km)	0.0113 kWh/km
Maximum speed (in km/h)	32 km/h

Note: Technical specifications of the e-cargo bike are extracted from BIEK (2017).

In addition, there are no restrictions regarding fleet size for each distribution centre. However, each distribution centre is initially assigned five (5) vehicles because it is assumed that additional vehicles should be generated when the need arises and the fact that delivery operations have a time window.

4.1.7. Emission Conversion Factors

Emission conversion factors are used to assess the amount of emissions the transport vehicles generate during the simulation. They help evaluate the environmental impacts of implementing the different logistics measures on last-mile delivery. The considered emissions are CO_2, CO, PM_{10}, HC and NO_X. The emission conversion factors are obtained from the work of Thaller (2018), except for the CO_2 conversion factor of electricity. The CO_2 conversion factor of electricity is obtained from the report of the Federal Environment Agency as 0.375 kg/kWh for 2020 (Icha et al., 2022). Generally, electric vehicles have zero CO_2 emissions, but some emissions are emitted during electricity production based on the well-to-wheel analysis.

Table 4.8 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	0.00028 g/m
PM_{10} Conversion Factor - Diesel	0.00090 g/m
HC + NO_X Conversion Factor - Diesel	0.00104 g/m

Note: The emissions conversion factors are obtained from the works of Thaller (2018) and Icha et al. (2022).

4.2. Definition of Key Performance Indicators for Analysis

The following key performance indicators are defined and used to analyse the simulation's results. They were obtained from the research works of Thaller (2018) and Adeniran (2020).

1. Total demand for goods per day: Total demand for goods per day is generated by the summation of the delivered parcels upon completion of the simulation.

$$tDG = \sum_{i=1}^{n} sh$$

Where:

tDG = Total demand for goods or delivered shipments (parcels/day)

sh = Shipment (parcel)

2. Total freight transport demand: Total freight transport demand is the total number of vehicles used daily to deliver parcels. The assumption here is that a vehicle can only carry out one tour per day, making this result corresponds to the number of tours completed.

$$tFTD = \sum_{i=1}^{n} T$$

Where:

$tFTD$ = Total freight transport demand (vehicles/day)

T = Tour (vehicles)

3. Total transport distance: Total transport distance is the sum of the distance travelled by all used vehicles. The links on which the utilised vehicles travel are determined using the road network. Then the overall transport distance is calculated by adding all the lengths of the identified links.

$$tTd = \sum_{i=1}^{n} L$$

Where:

tTd = Total transport distance (metres/day)

L = Length of link (metres)

4. Total transport duration per day: Total transport duration per day refers to the total time it takes the complete fleet of vehicles to deliver the parcels to customers (both private and commercial). Each vehicle in the simulation accumulates this transit duration. The calculation takes the dispatch time from the distribution centre and subtracts it from the entry time at the distribution centre.

$$tTT = \sum_{i=1}^{n} \left(T_{arr} - T_{dep}\right)$$

Where:

tTT = Transport duration per day (seconds/day)

T_{arr} = Arrival time at the distribution centre (seconds)

T_{dep} = Departure time at the distribution centre (seconds)

5. Fixed transport costs per day: The total fixed transport costs per day refer to the product of the total freight transport demand and the fixed transport costs per vehicle.

$$FC_{day} = tFTD \times FC_{veh}$$

Where:

FC_{day} = Fixed transport costs per day (€/day)

$tFTD$ = Total freight transport demand per day (vehicles/day)

FC_{veh} = Fixed transport costs per vehicle (€/vehicle)

6. Variable transport costs per day: The total variable transport costs per day refer to the product of total transport distance and the variable transport costs incurred per vehicle.

$$VC_{day} = tTd \times VC_m$$

Where:

VC_{day} = Variable transport costs per day (€/day)

tTd = Total transport distance (metres/day)

VC_m = Variable transport costs per metre (€/metre)

7. Personnel transport costs per day: Personnel transport costs per day refer to the product of total transport time and the personnel costs per second.

$$PC_{day} = tTT \times PC_s$$

Where:

PC_{day} = Personnel costs per day (€/day)

tTT = Transport duration per day (seconds/day)

PC_s = Personnel transport costs per second (€/second)

8. Total transport Costs per day

$$tTC_{day} = FC_{day} + VC_{day} + PC_s$$

Where:

tTC_{day} = Total transport costs per day (€/day)

FC_{day} = Fixed transport costs per day (€/day)

VC_{day} = Variable transport costs per day (€/day)

PC_s = Personnel transport costs per day (€/day)

9. Fuel consumption per day

$$FL_{day} = tTd \times FL_m$$

Where:

FL_{day} = Fuel consumption per day (litres/day)

tTd = Total transport distance (metres/day)

FL_m = Fuel consumption per metre (litres/metre)

10. AdBlue consumption per day

$$AB_{day} = tTd \times AB_m$$

Where:

AB_{day} = AdBlue Consumption per day (l/day)

tTd = total transport distance (metres/day)

AB_m = AdBlue consumption per metre (litres/metre)

11. CO_2 emissions per day

$$CO_{2\ day} = FL_{day} \times \beta_D + AB_{day} \times \beta_{AB}$$

Where:

$CO_{2\ day}$ = CO_2 emissions per day (kg/day)

FL_{day} = Fuel consumption per day (litres/day)

β_D = CO_2 conversion factor for fuel type (kg/litre) or (kg/kWh)

AB_{day} = AdBlue consumption per day (l/day)

β_{AB} = CO_2 conversion factor for AdBlue (kg/litre)

12. Other emissions per day (CO, PM_{10}, HC and NO_X)

$$EM_{i,day} = tTd \times \beta_i$$

Where:

$EM_{i,\ day}$ = Type i emissions per day (g/day)

tTd = Total transport distance (metres/day)

β_i = Conversion factor for emission type i per metre (g/metre)

4.3. Scenarios Definition

The scenarios are underlined after the data preparation and declaration of analysis variables. However, crowdsourcing and autonomous vehicle applications for freight delivery operations, particularly the last-mile delivery, are not taken into account in the scenario development due to their dynamic scope and their unclear futures, respectively. Hence, the selected logistics measures for last-mile delivery within the study area are diesel trucks (which serve as the base scenario), electric trucks, e-cargo bikes with micro-depots, parcel shops and parcel lockers. Thus, the modelled scenarios are:

Scenario 0: Baseline Scenario

The baseline scenario involves using diesel trucks for last-mile delivery and serves as a standard to analyse the other scenarios. Diesel trucks deliver parcels directly to customers (private and commercial) from distribution centres. Here, it is assumed that all private customers choose home delivery. Table 4.9 contains additional information on the diesel truck utilised regarding loading capacity and transport costs' elements.

Table 4.9 Calculated Attributes of the Diesel Trucks

Parameters	Values
Maximum loading capacity	160 parcels/truck
Fixed costs	45.497791235 €/day
Variable costs	0.000335575 €/m
Personnel costs	0.004200975 €/s
Energy consumption	0.000086 l/m
AdBlue consumption	0.0000015 l/m

Scenario 1: Electric trucks

Scenario 1 involves using electric trucks for last-mile delivery, which is quite similar to the base scenario, but the difference is that electric trucks are utilised here. Table 4.10 contains additional information on the loading capacity and transport cost elements of the electric truck used.

Table 4.10 Calculated Attributes of the Electric Trucks

Parameters	Values
Maximum loading capacity	115 parcels/truck
Fixed costs	52.385364559 €/day
Variable costs	0.000372839 €/m
Personnel costs	0.004200975 €/s
Energy consumption	0.000296 kWh/m

Scenario 2: E-Cargo Bikes with Micro-depots

Here, electric trucks transport parcels to micro-depots, and e-cargo bikes deliver to private customers. This concept involves a two-step delivery process. B2C parcels are first transferred directly to micro-depots from distribution centres by electric trucks, from which the parcels are directly delivered to private consumers utilizing e-cargo bikes from micro-depots. B2B deliveries are still made directly to commercial customers by electric trucks. Additional details on the utilized e-cargo bike's carrying capacity and transportation costs are provided in Table 4.11.

Table 4.11 Calculated Attributes of the E-Cargo Bikes

E-Cargo Bike Parameters	Values
Maximum loading capacity	30 parcels/cargo bike
Fixed costs	3.1347222 €/day
Variable costs	0.0002581 €/m
Personnel costs	0.0032315 €/s
Electricity consumption	0.0000113 kWh/m

Scenario 3: Use of Parcel Shops and Parcel Lockers

Parcel shops and parcel lockers are combined in one scenario to maximise their collective benefits. This concept also has a two-step delivery process. Firstly, electric trucks transport B2C parcels from distribution centres to parcel shops and parcel lockers closest to the private customer. Private customers must then walk some distance to receive their parcels from the parcel shops or parcel lockers. While B2B deliveries are still directly delivered to commercial customers by electric trucks. For private customers, the last-mile delivery is fulfilled once the parcels arrive at the closest parcel shop or parcel locker to the customer.

5. Results

Upon the completion of each scenario's simulation run, results were generated. This aids in the quantitative analysis of the logistics measures of CEP service providers to assess their suitability for last-mile delivery in small- and medium-sized cities. The simulation results are generated as output for a day of logistical activities. The results are calculated based on the equations of the key performance indicators defined in section 4.2.

5.1. Baseline Scenario

The usage of diesel trucks for last-mile delivery by CEP service providers in the Städteregion Aachen resulted in 577 tours. That is, 577 diesel trucks deliver all B2C and B2B parcels directly from the distribution centres to private and commercial customers per day, respectively. As a result, all vehicles covered a total freight distance of 91,421.81 kilometres with an average freight distance of 158.44 kilometres per tour, and 7,862.28 litres of diesel was consumed.

Table 5.1 Baseline Scenario Indicators

Indicators	**Values**
Number of tours required	577
Total freight distance travelled	91421.81 km
Average freight distance travelled per tour	158.44 km
Energy consumption	7862.28 l
Fixed costs	€ 26,252.23
Variable costs	€ 30,678.87
Personnel costs	€ 39,287.76
Total transport costs	€ 96,218.86
CO_2 emissions	20.70 kg
CO emissions	25.42 g
PM_{10} particles	8.25 g
HC + NO_X emissions	95.46 g
Average lead time per tour	7.91 h
Average road speed	7.11 m/s
Average number of stops per tour	57
Average transport cost per tour	€ 166.76

A total transport cost of 96,218.86 Euros was incurred from operating with this logistics measure, which includes total fixed costs of 26,252.23 Euros, total variable costs of 30,678.87 Euros and total personnel costs of 39,287.76 Euros. The environmental impacts observed are 20.7 kilograms of carbon dioxide emissions, 25.42 grams of carbon monoxide emissions, 8.25 grams of PM_{10}, and 95.46 grams of HC and NO_X

emissions. In addition, other noteworthy observations include average transport costs per tour of 166.76 Euros, the average number of stops per tour of 57, and the average road speed of the network, which is 7.11 metres per second. Furthermore, an average lead time per tour of 7.9 hours was observed, i.e., this includes the entire trip from the distribution centre and back to the distribution centre.

The baseline scenario's results served as the yardstick to compare other scenarios. Each scenario is evaluated regarding freight distance travelled, number of tours required, energy consumption, transportation costs and environmental impacts.

5.2. Results of Scenarios Analysis

5.2.1. Number of Tours Required

The number of tours required to carry out the last-mile of all freight goods (B2B and B2C) equals the number of vehicles needed, as defined in section 4.2. A freight tour refers to the delivery activity of a vehicle, containing several parcels based on its payload capacity from the distribution centre and back to the distribution centre. For scenarios 1, 2 and 3, the number of tours required to fulfil the daily freight demands is higher than that of scenario 0, as shown in Figure 5.1. The number of tours required for scenario 0 is 577 tours. While scenario 1 required 28.9% more tours than scenario 0, scenario 2 required 284.8% more tours than scenario 0, and scenario 3 required 32.1% more tours than scenario 0. Scenario 2 has the highest number of tours, with 682 tours made by electric trucks and 1538 tours made by e-cargo bikes.

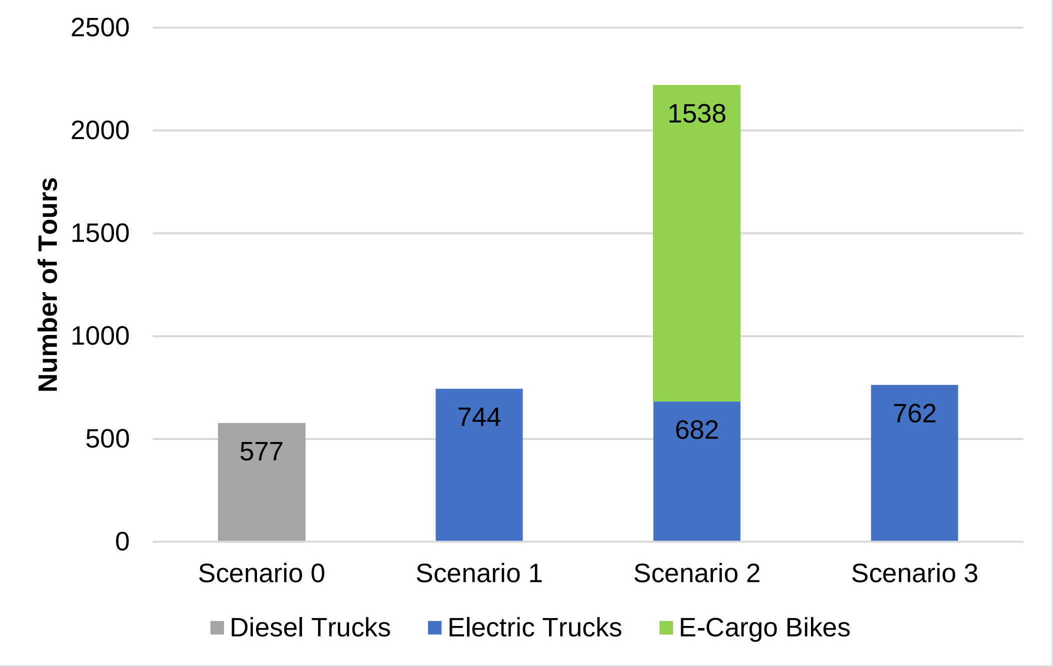


Figure 5.1 Number of Tours Required

The differences regarding the number of tours needed for each scenario can be related to the used vehicles' payload capacity. The diesel truck model used in this research has the highest payload capacity compared to the electric truck and e-cargo bike models. The diesel trucks have a payload capacity which is 48% more than the payload capacity of the electric trucks (as defined in Table 4.6) and 511% more than the payload of e-cargo bikes (as defined in Table 4.7). Therefore, more tours are necessitated to fulfil the same quantity of daily freight demand. Scenario 2, which is a two-step delivery process, used two vehicle types and required the e-cargo bikes to initiate another tour from the micro-depots to the private customers.

5.2.2. Total Freight Distance Travelled

The total freight distance travelled refers to the sum of distances travelled by all freight vehicles while carrying out the last-mile delivery. The unit of the total freight distance travelled per day is kilometres. Scenario 0 is observed to have a total freight distance of 91,421.81 kilometres, while that of scenario 1 increased by 30.9%. The increase in total freight distance travelled in scenario 1 is due to the increased number of needed electric trucks, prompted by lesser payload capacity compared to diesel trucks to fulfil the daily freight demand.

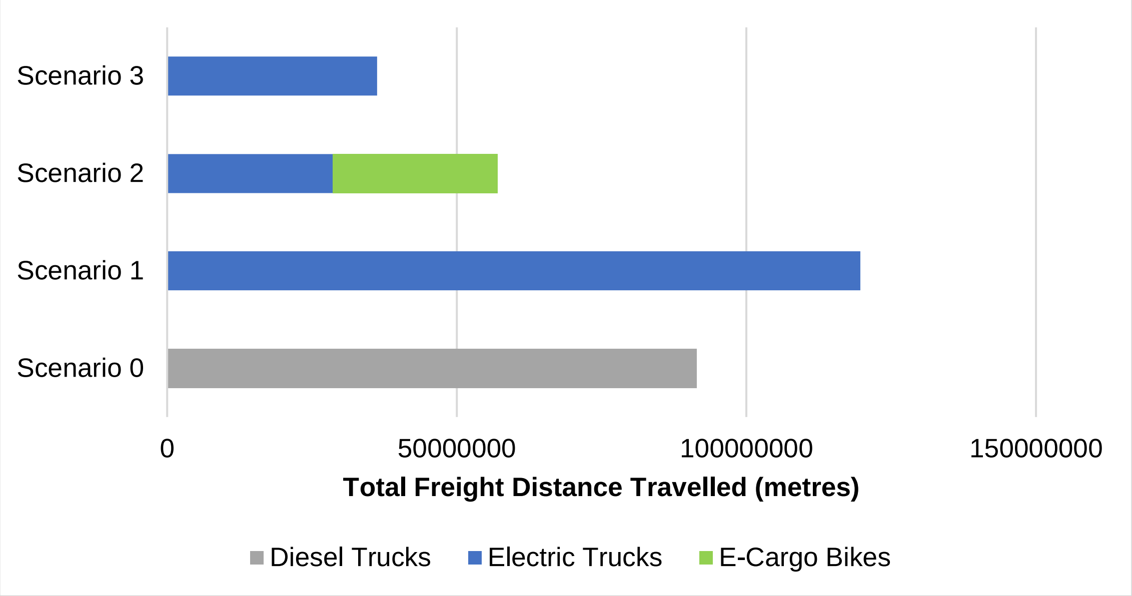


Figure 5.2 Total Freight Distance Travelled

Note: In scenario 3, walking distance of private customers to parcel shops and parcel lockers is not included.

The total freight distance travelled in scenarios 2 and 3 are 37.6% and 60.4% lower than in scenario 0, respectively. And the decrease in the total freight distance in scenarios 2 and 3, even though the number of tours required increased, is due to the two-step delivery process. The two-step delivery process allows for better vehicle routing optimisation because fewer customers are served per tour. As a result, the average number of stops per tour decreases from 57 in scenario 0 to 15 in scenario 2 and 7 in scenario 3, i.e., a reduction of 73.7% and 87.7%, respectively. Additionally, in scenario 3, fewer distances are covered because B2C parcels are delivered to parcel shops and parcel lockers rather than home deliveries. In scenario 3, the walking distance of private customers to the parcel shops and parcel lockers is not considered and is not included in the calculated total freight distance travelled. In scenario 2, the total freight distance covered by electric trucks is 28,615 kilometres, and that by e-cargo bikes is 28,446 kilometres.

5.2.3. Average Freight Distance Travelled

The average freight distance travelled is the total freight distance travelled divided by the number of tours performed. Similar to the total freight distance travelled, scenarios 2 and 3 reduced significantly regarding the average freight distance travelled compared with scenario 0. The reduction in scenarios 2 and 3 are 61.8% and 70%, respectively. The reduction in scenarios 2 and 3 is because of the high number of tours performed in these scenarios, which were prompted by the limited payload capacity of the vehicles used (electric trucks and e-cargo bikes). The average freight distance travelled for scenario 0 is 158.44 kilometres, and scenario 1 is 1.5% higher than scenario 0, as shown in Figure 5.3. In scenario 2, the average freight distance covered by electric trucks is 41.96 kilometres, and that by e-cargo bikes is 18.5 kilometres.

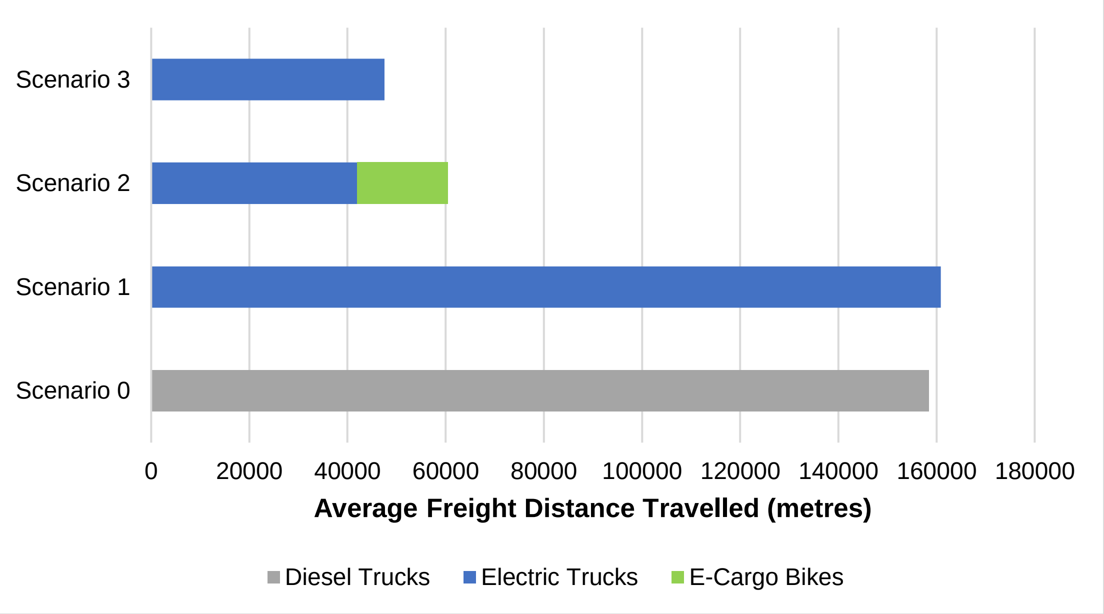


Figure 5.3 Average Freight Distance Travelled

Note: In scenario 3, walking distance of private customers to parcel shops and parcel lockers is not included.

5.2.4. Energy Consumption and Costs

Energy consumption is an important indicator which influences the total operating costs and emissions based on the fuel type. Diesel and electricity are the two energy sources that are considered based on the types of vehicles used in the scenarios. The energy consumption is assessed using the energy cost, as indicated in Figure 5.4, as these two fuel sources have distinct measurement units. Total energy cost is calculated as the product of the quantity of energy consumed per day and the unit price of the fuel and is expressed as Euros per day. The energy consumptions are 7862.3 litres of diesel in scenario 0, 35424.5 kilowatt-hours of electricity in scenario 1, and 10722.6 kilowatt-hours of electricity in scenario 3. In scenario 2, 8791.6 kilowatt-hours of electricity was consumed, resulting from 8470.2 kilowatt-hours of electricity by electric trucks and 321.4 kilowatt-hours of electricity by e-cargo-bikes.

Regarding energy costs, the energy used in scenario 0 equates to 10,063.71 Euros. On the other hand, the total energy costs used in scenario 1 is 5.6% higher than scenario 0, while scenarios 2 and 3 are reduced by 73.8% and 68%, respectively, compared with scenario 0. Scenario 2 has the lowest energy costs because of electricity cost per unit kilowatt-hour is cheaper than one litre of diesel, and e-cargo bikes do not consume much energy.

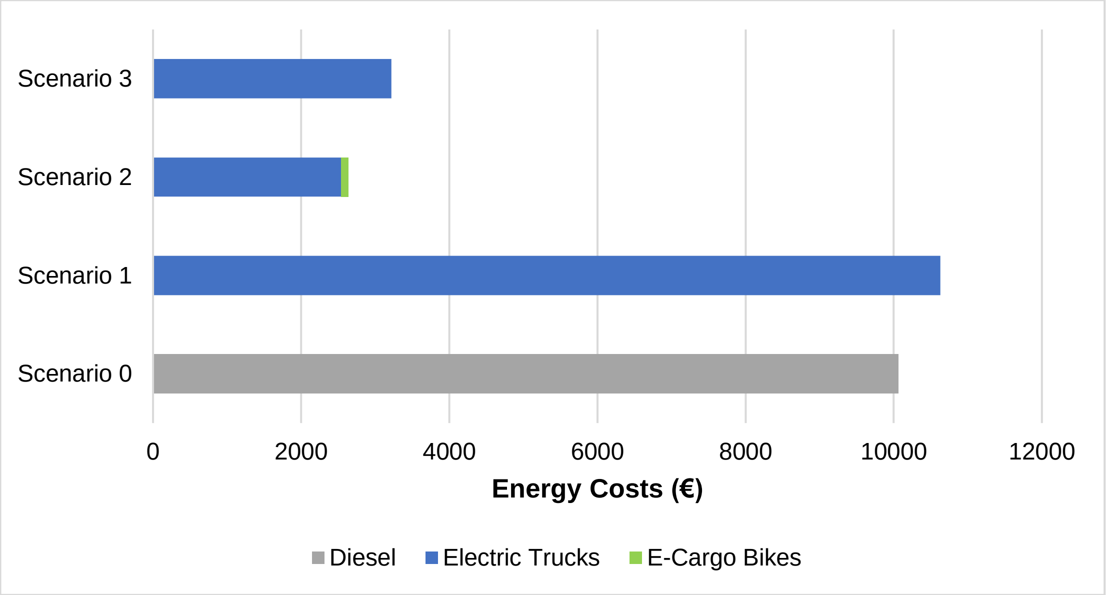


Figure 5.4 Energy Costs

5.2.5. Fixed Costs

Fixed costs are incurred costs that are not influenced by an increase or decrease in goods or services rendered. The total fixed cost of each scenario is calculated using the estimated fixed costs of all vehicles utilised in the scenario, as defined in section 4.2.

The fixed cost of each vehicle, as shown in Table 4.9, Table 4.10 and Table 4.11, are estimated based on purchasing cost, depreciation, interest costs, motor vehicle tax, insurance, and other fixed vehicle costs. These costs are expressed in Euros per day and correlate with the number of vehicles used. The total fixed costs incurred in the scenarios per day are 26,252.2 Euros in scenario 0, 38,974.7 Euros in scenario 1, 40,548 Euros in scenario 2 (35,727 Euros by electric trucks and 4,821 Euros by e-cargo bikes), and 39,917.7 Euros in scenario 3. That is, there is an increment of 48.5% in scenario 1, 54.5% in scenario 2 and 52.1% in scenario 3 when each is compared with scenario 0.

The increase in fixed costs in scenarios 1, 2 and 3 is related to the fact that electric vehicles are more expensive than conventional internal combustion vehicles. For instance, the electric truck model used in scenarios 1, 2 and 3 is more expensive than the diesel truck model used in scenario 0, even though they have the same total permissible weights. It is important to note that the fixed costs of building the micro-depots are not considered in the calculation of total fixed costs in scenario 2. Similarly, the fixed costs associated with operating the parcel lockers are not considered in scenario 3.

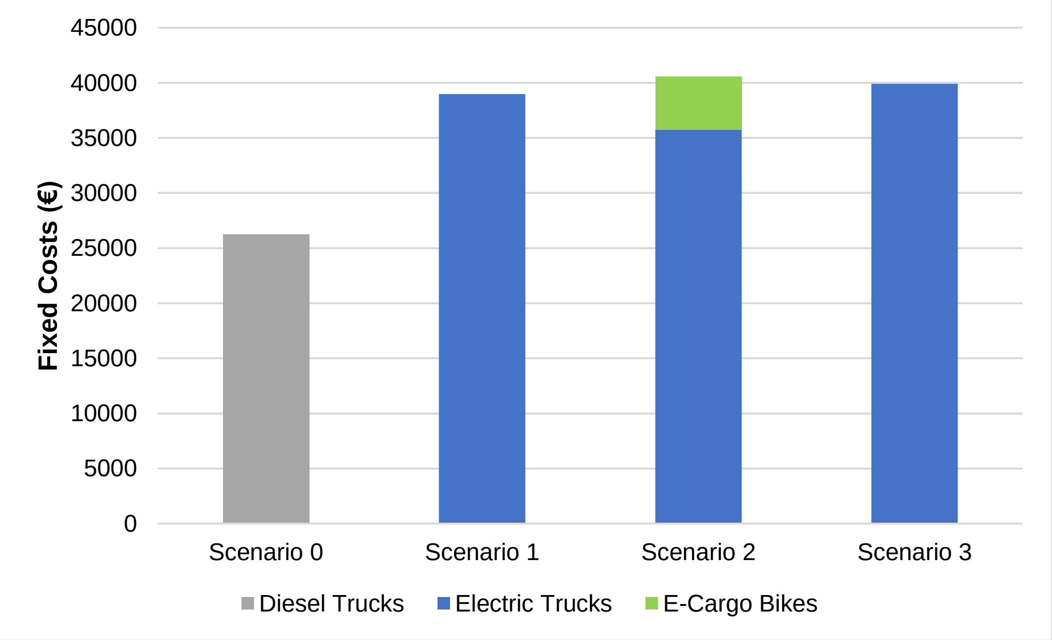


Figure 5.5 Total Fixed Costs

5.2.6. Variable Costs

Variable costs are costs that are influenced by the number of goods or services rendered. In the case of last-mile delivery, it is mainly influenced by freight distance travelled. The total variable cost of each scenario is calculated using the total freight distance travelled (metres/day) and the estimated variable costs (€/metre) of all vehicles utilised in the scenario as defined in section 4.2. The variable cost of each vehicle, as shown in Table 4.9, Table 4.10 and Table 4.11, are estimated based on the workshops and maintenance costs, tyre costs and fuel costs.

In scenarios 0, 1, 2, and 3, the total variable costs are 30,678.9 Euros, 44,620.4 Euros, 18,011 Euros, and 13506.1 euros, respectively, as shown in Figure 5.7. Scenario 3 has the lowest variable costs, which is a 56% decrease from Scenario 0. Compared to scenario 0, scenarios 1 and 2 showed a 45.4% increase in total variable costs and a 41.3% decrease in total variable costs, respectively. The total variable costs incurred in scenario 2 is the summation of 10,669 Euros from using electric trucks and 7,342 Euros from using e-cargo bikes. Variable costs increase or decrease as the total distance travelled increases or decreases. It is important to note that the variable costs associated with operating and maintaining the facilities of micro-depots, parcel shops and parcel lockers are not considered in the total variable costs of scenarios 2 and 3.

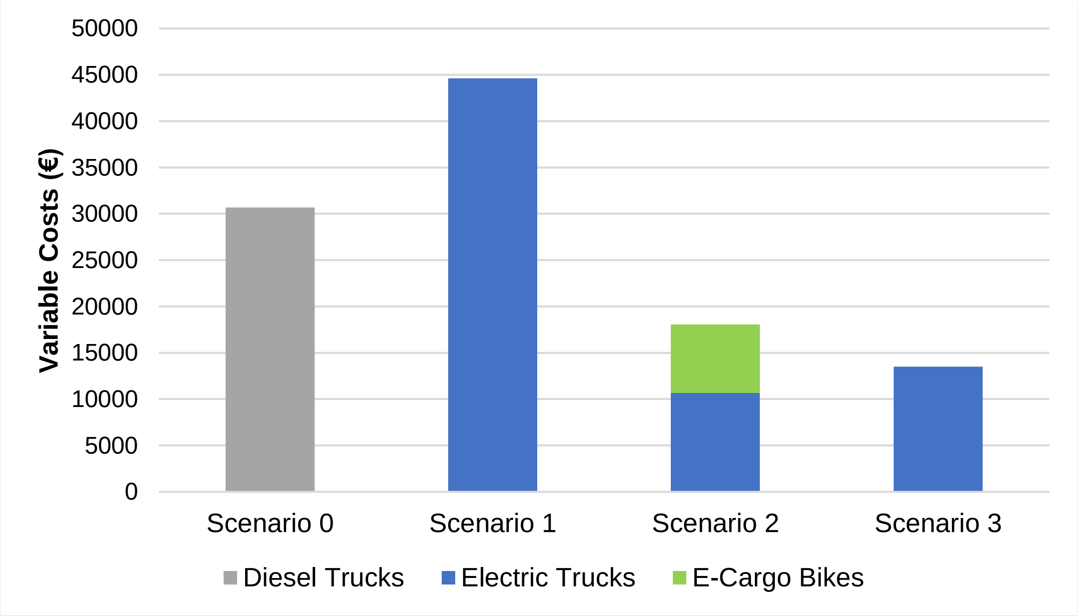


Figure 5.6 Total Variable Costs

5.2.7. Personnel Costs

Personnel costs refer to costs associated with wages of employed persons for their services rendered in carrying out the last-mile delivery, e.g., drivers of the trucks and riders of the e-cargo bikes. The total personnel cost of each scenario is calculated as the product of the total driving time per day (seconds/day) and the estimated personnel costs per second (€/s) of all vehicles used in the scenario as defined in section 4.2. Personnel cost is a time-varying cost which is also influenced by the total freight distance covered. The total personnel costs are 39,287.8 Euros in scenario 0, 48,997.6 Euros in scenario

1, 24,012.8 Euros in scenario 2, and 12738.3 Euros in scenario 3, as shown in Figure 5.7. The total personnel cost incurred in scenario 2 is the sum of 10,056 Euros from using electric trucks and 13,957 Euros from using e-cargo bikes. In scenario 2, the total personnel cost incurred from utilising e-cargo bikes is higher than that of electric trucks because of the large number of e-cargo bikes used.

Similar to the variable costs, scenario 3 has the lowest total personnel costs, which is a 67.6% decrease from scenario 0. On the other hand, scenario 1 has a 24.7% increase in total personnel costs and scenario 2 has a 38.9% decrease in total variable costs compared to scenario 0. It is important to note that the personnel costs associated with operating and maintaining the facilities of micro-depots, parcel shops and parcel lockers are not considered in the total personnel costs of scenarios 2 and 3.

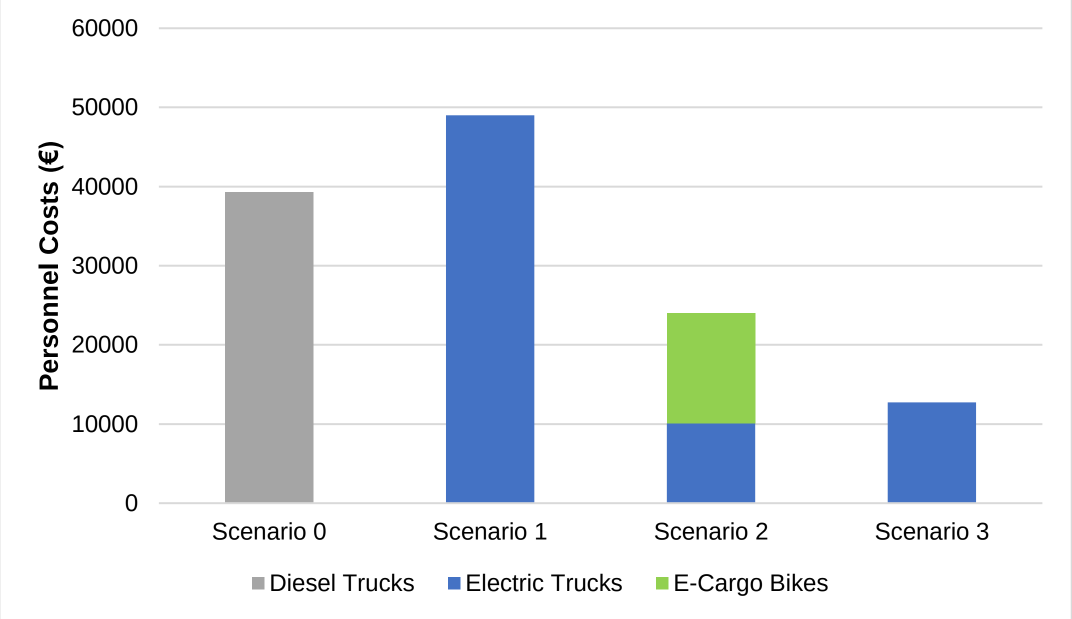


Figure 5.7 Total Personnel Costs

5.2.8. Total Transport Costs

The total transport cost is the summation of the fixed costs, variable costs and personnel costs per scenario. Scenario 1 has the highest total transport cost, which is 132,592.7 Euros, and this is a 37.8% increase from the baseline scenario (i.e., scenario 0), which is 96,218.9 Euros. On the other hand, compared to scenario 0, scenarios 2 and 3 showed a 14.2% decrease in total transport costs and a 31.2% decrease in total transport costs, respectively. Therefore, scenario 3 has the lowest total transport costs, as shown in Figure 5.8. The total transport cost incurred in scenario 2 is the sum of 56,452 Euros from using electric trucks and 26,120 Euros from using e-cargo bikes.

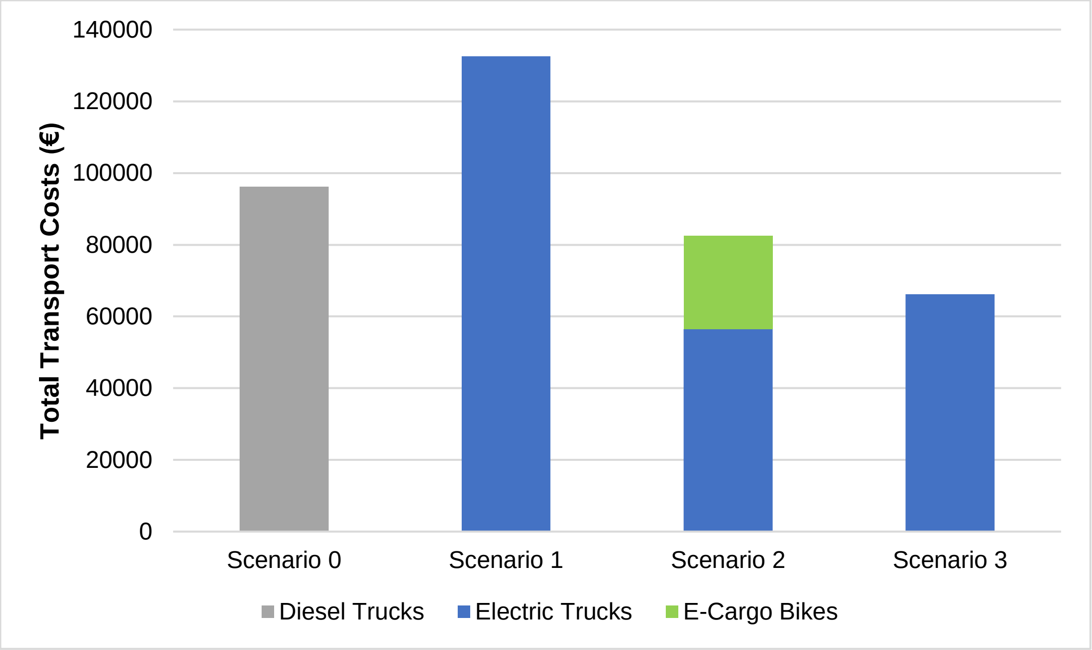


Figure 5.8 Total Transport Costs

5.2.9. Environmental Impacts

The environmental impacts of using each modelled logistics measure for last-mile delivery are assessed based on the CO_2 emissions, CO emissions, PM_{10}, and HC and NO_X emissions, as indicated in section 4.2. Observing the environmental impacts is essential to avoid using logistics measures that harm the environment. While the concern of a liveability society is the government's focus, most cities have government policies to ensure that the freight activities of CEP service providers are not detrimental to the environment.

Carbon dioxide (CO_2) is not considered an air pollutant as it is a naturally occurring element in the atmosphere. However, it becomes a pollutant when its emission quantity negatively impacts the environment, as observed worldwide today. Increasing CO_2 emissions into the atmosphere are due to several human activities, such as road transportation. CO_2 is a greenhouse gas, and as greenhouse gas emissions increase, average temperatures rise along with them, warming the earth's climate (resulting in global climate change). It is noteworthy that electric vehicles (electric trucks and e-cargo bikes) do not emit CO_2 emissions. However, using the well-to-wheel analysis, the CO_2 emitted during electricity production is considered.

The equation described in section 4.2 is used to calculate the CO_2 emissions for each scenario, and Table 4.8 lists the CO_2 emission conversion factors for diesel and electricity. Scenarios 1, 2 and 3 have lower CO_2 emissions than scenario 0 because electric vehicles are used in these scenarios, while diesel trucks are used in scenario 0. Scenario 1 has a 35.8% decrease in CO_2 emissions in contrast to scenario 0, while scenarios 2 and 3 have an 84.1% decrease and 80.6% decrease in CO_2 emissions, respectively, as shown in Figure 5.9. This reflects one of the benefits of electric vehicles over diesel vehicles in terms of their sustainable prospects as a logistics measure. In scenario 2, as indicated in Figure 5.9, e-cargo bikes emit very low CO_2 emissions. The amount of CO_2 emissions emitted by e-cargo bikes in scenario 2 is 0.12 kilograms, whereas electric trucks emitted 3.18 kilograms.

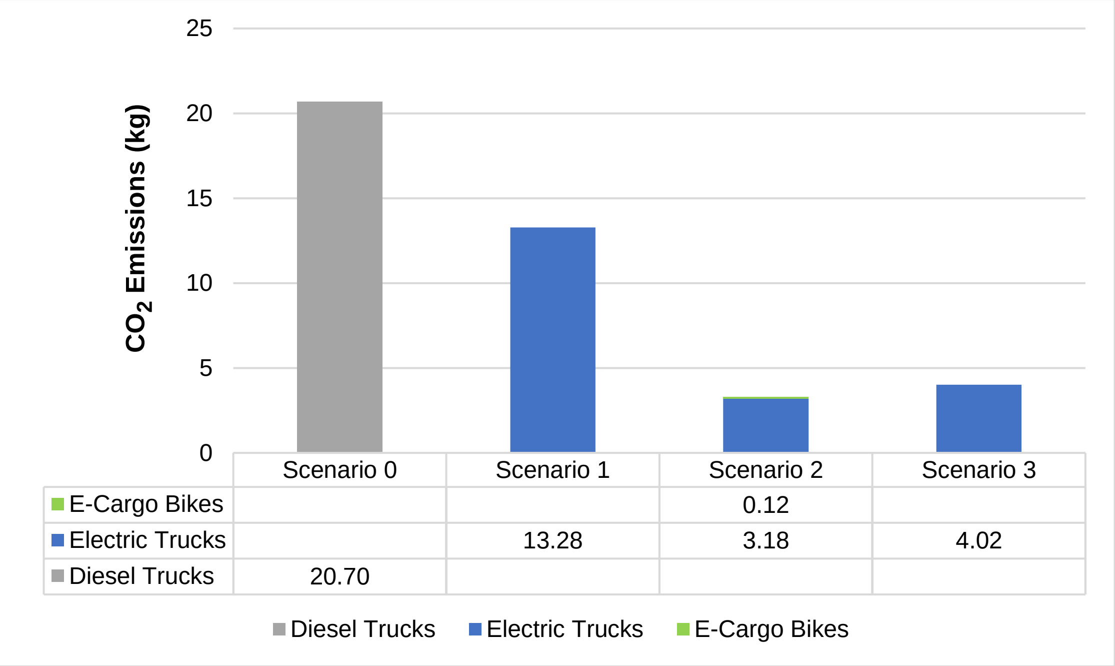


Figure 5.9 CO_2 Emissions

CO emissions, PM_{10}, HC and NO_X emissions are air pollutants that conventional internal combustion vehicles emit. The emissions of these pollutants do affect the air quality. Electric vehicles do not emit CO, HC and NO_X because their combustion process is free of these harmful emissions (OECD, 2020). Therefore, electric trucks and e-cargo bikes emit no CO emissions, HC and NO_X emissions. PM_{10} are very small particles found in the dust (e.g., dust from roads or construction sites), smoke (e.g., smoke from cars or waste burning), mines, etc. PM_{10} emissions from electric vehicles can be estimated using tyre wear, road wear and road dust resuspension. According to a study by OECD (2020), PM_{10} emissions from electric vehicles are 11-19% lower than those of conventional internal combustion vehicles such as diesel trucks. However, there is still ambiguity over the quantity of PM_{10} emitted from non-exhaust sources in actual driving circumstances. Many factors, including vehicle weight, the material composition of brakes, tyres, and roads, the amount of dust on road surfaces, and driving habits, affect how much particulate matter a vehicle generates. Hence, the amount of PM_{10} emitted from using electric trucks and e-cargo bikes in scenarios 1, 2 and 3 are not estimated.

The CO emissions, PM_{10} particles, HC and NO_X emissions from diesel trucks used in scenario 1 are estimated using the emission conversion factors, stated in Table 4.8, and the total freight distance travelled, as indicated in section 4.2. In scenario 0, the environmental impacts include 25.42 grams of CO emissions, 8.25 grams of PM_{10}, and 95.46 grams of HC and NO_X emissions. Hence, scenarios 1, 2 and 3 are significantly better than scenario 0 in terms of CO, HC and NO_X emissions because they are 100% reduced.

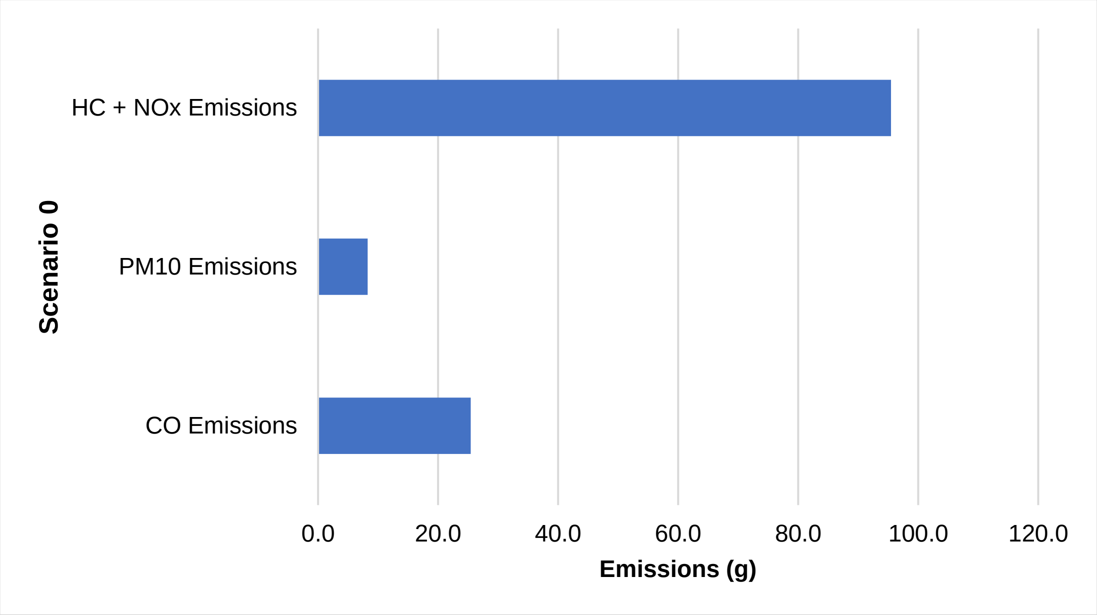


Figure 5.10 CO, PM_{10}, HC and NO_X emissions of Scenario 0

5.2.10. Other Indicators

The average road speed, average lead time per tour and average transport cost per tour are other noteworthy indicators. The average road speed in scenario 0 is 7.11 metres per second. The average road speed in scenario 1 is also 7.11 metres per second, decreased by 5.9% to 6.69 metres per second in scenario 2 and increased by 27.8% to 9.08 metres per second in scenario 3. Even though the e-cargo bikes in scenario 2 use the cycling paths, the electric trucks still affected the road traffic flow. Compared to scenario 0, the road network's condition is better in scenario 3 since less total freight distance was travelled, even though more electric trucks were utilised. Therefore, scenario 3 improved the traffic state of the road network and has the best impact in terms of average speed.

Scenarios 1, 2 and 3 have a better average lead time per tour than scenario 0. The average lead time per tour is the sum of all driving and stopping times from the distribution centre and back to the distribution centre, divided by the number of freight tours. The average lead time per tour is 7.9 hours in scenario 0, 7 hours in scenario 1 (11.5% reduction), 1.9 hours in scenario 2 (74.9% reduction) and 2.2 hours in scenario 3 (73% reduction). The significant reduction in average lead time per tour in scenarios 2 and 3 is equally influenced by the two-step delivery process. In addition, using the micro-depots allows for better vehicle routing solutions since fewer private customers are served per tour. The average transport cost per tour in scenarios 0, 1, 2 and 3 are 166.8 Euros, 178.2 Euros, 37.2 Euros and 86.8 Euros, respectively. Scenario 2 has the lowest average transport cost per tour.

6. Discussion

For last-mile delivery in small- and medium-sized cities, CEP service providers tend to be less innovative and consider diesel trucks are the most viable logistics measure. Therefore, an empirical analysis was performed to analyse the logistics measures available to CEP service providers and the feasibility of each in small- and medium-sized cities using the agent-based transport simulation MATSim and the integrated logistics behaviour model jsprit. In addition, scenario 0 (the baseline scenario), which depicts the use of diesel trucks, was compared against other selected relevant logistics measures for last-mile delivery in small- and medium-sized cities.

The selection of relevant logistics measures were based on literature reviews, and they are the use of electric trucks (scenario 1), the use of e-cargo bikes in conjunction with micro-depots (scenario 2) and the use of parcel shops and parcel lockers (scenario 3). The comparisons between the scenarios are made based on the main findings of this research, as shown in Table 6.1. Table 6.1 summarises the evaluation comparison of all four scenarios of logistics measures. Scenario 0 results are used as a yardstick to compare the other three scenarios for each indicator under consideration. The result values are expressed as percentages, with the standard value for scenario 0 displayed as 0%. Positive percentages are used to indicate improved results in scenarios 1, 2, and 3, while negative percentages are used to indicate decreasing results.

Recently, electric trucks (scenario 1) have been advocated 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 (scenario 0), as indicated in Table 6.1. The total transport costs and its components in scenario 1, i.e., fixed costs, variable costs and personnel costs, are higher than those of scenario 0. More electric trucks are also required because of their low payload capacity in comparison to the payload capacity of diesel trucks. More tours equally resulted in more freight distance travelled by the electric trucks, but there was no significant impact on the road network compared to scenario 0 in terms of average road speed. The implementation of scenario 1 is observed to incur more energy costs than scenario 0. However, scenario 1 still has some benefits, such as significant environmental benefits, reduced average lead time per tour and reduced average transport costs per tour. In addition, electric trucks provide higher environmental benefits than diesel trucks because they emit fewer CO_2 emissions and no CO, HC and NO_X emissions.

Scenario 2 involves using e-cargo bikes and micro-depots to deliver B2C parcels to private customers. Electric trucks are still utilised in this scenario to deliver B2B parcels to commercial customers and to transport B2C parcels to micro-depots. In Scenario 2, the two-step delivery process led to a considerable increase in the number of tours carried out. Compared to scenario 0, there is a 284.8% increase in freight tours, but the total freight distance travelled decreased by 37.6% because each tour has fewer stops. The average number of stops decreased by 73.7% compared to the usage of diesel trucks, which also significantly reduced the average lead time. Due to the lower cost of electricity than diesel and the shorter freight mileage covered, the cost of energy consumed also decreased by 73.4%. These findings are consistent with the studies of Hofmann et al. (2017), Stodick & Deckert (2019), and Llorca & Moeckel (2020).

Table 6.1 Scenarios Comparison

Indicators	**Scenario 0**	**Scenario 1**	**Scenario 2**	**Scenario 3**
Number of Tours required	0%	28.94%	284.75%	32.06%
Total freight distance travelled	0%	30.91%	-37.58%	-60.38%
Average freight distance travelled per tour	0%	1.52%	-61.84%	-70.00%
Energy Costs	0%	5.60%	-73.79%	-68.04%
Fixed costs	0%	48.46%	54.46%	52.05%
Variable costs	0%	45.44%	-41.29%	-55.98%
Personnel costs	0%	24.71%	-38.88%	-67.58%
Total transport costs	0%	37.80%	-14.18%	-31.24%
CO2 emissions	0%	-35.83%	-84.08%	-80.58%
CO emissions	0%	-100.00%	-100.00%	-100.00%
HC + NOx emissions	0%	-100.00%	-100.00%	-100.00%

Note: Green-coloured percentages with a minus (-) are used to indicate improved results, while red-coloured percentages are used to indicate decreasing results.

The total transport costs in scenario 2 decreased by 14.2%, as shown in Table 6.1. This finding is also consistent with the study of Zhang et al. (2018). Furthermore, even though total fixed costs increased by 54.5% compared to scenario 0 due to the increase in the number of vehicles used and purchasing price of electric trucks, total variable and personnel costs decreased by 41.3% and 38.9%, respectively, because of the decrease in total freight mileage. As a result, scenario 2 showed a significant reduction in negative environmental impacts with an 84.1% decrease in CO_2 emissions and a 100% decrease in CO, HC and NO_X emissions. This finding is also consistent with the studies of Hofmann et al. (2017), Melo & Baptista (2017), Rudolph et al. (2018), Zhang et al. (2018), Stodick & Deckert (2019), and Narayanan & Antoniou (2021).

Scenario 3 involves the usage of parcel shops and parcel lockers for B2C deliveries and electric trucks for B2B deliveries to transport freight goods from the distribution centres to the micro-depots. The number of tours in scenario 3 is 762, which is a 32.1% increase compared to scenario 0. Similar to scenario 2, there is a significant reduction in total freight mileage covered, energy costs, transport costs, and environmental impacts in scenario 3. Compared to scenario 0, there is a 60.4% decrease in total freight mileage, a 68% decrease in energy costs, a 31.2% decrease in total transport costs, an 80.6% decrease in CO_2 emissions, and a 100% decrease in CO, HC and NO_X emissions in scenario 3. Therefore, scenario 3 is the most cost-effective logistics measure. Scenario 3 also improved the condition of the road network in terms of average road speed by 5.9%, i.e., increasing it from 7.11 metres per second in scenario 0 to 9.08 metres per second.

Generally, scenarios 1, 2 and 3 emitted fewer emissions compared to scenario 0, which used diesel trucks. The emissions results showed the environmental benefits of electric vehicles (electric trucks and e-cargo bikes) compared to conventional internal combustion vehicles. This finding is consistent with the studies of Juan et al. (2016), Nicolaides et al. (2017), Stodick & Deckert (2019), Bac & Erdem (2021), and Mehmedi (2021). Scenario 2 is the best logistics measure regarding energy consumption and environmental impacts, with an 84.1% decrease in CO_2 emissions and a 100% decrease in CO, HC and NO_X emissions. Whereas scenario 3 is the best logistics measure in terms of total freight distance travelled and total transport costs, with a significant decrease of 60.4% in total freight distance travelled and 31.4% in total transport costs.

A notable concern in scenario 2 and scenario 3 is the high increase in the number of tours required, which is equal to the number of vehicles used. The number of vehicles used is assumed to be equal to the number of freight tours, as established in section 4.2. Although, an increase in the number of tours is not an issue because the total transport costs incurred while fulfilling the tours decreased compared to scenario 0. Based on the assumption, the recorded increase in the number of vehicles used will warrant CEP service providers to significantly increase their fleets of vehicles, which could be costly. However, the recorded number of vehicles cannot be translated into an actual need to increase vehicle fleets because of the assumption made. With due consideration of the average lead time per tour in scenarios 2 and 3 coupled with an efficient optimisation schedule, a vehicle used in scenarios 2 and 3 can perform more than one tour per day.

Using only electric trucks for last-mile delivery in small- and medium-sized cities is not cost-effective. However, electric trucks can be integrated for B2B deliveries to commercial customers and transport freight goods to micro-depots or parcel shops and parcel lockers as modelled in scenarios 2 and 3, respectively. The use of e-cargo bikes with micro-depots, and parcel shops and parcel lockers are feasible logistics measures for last-mile delivery in small- and medium-sized cities, such as the municipalities in the Aachen city region (Städteregion Aachen). As Stodick & Deckert (2019) pointed out, some cities require a mix of various logistics measures for operational efficiency, e.g., e-cargo bikes in conjunction with micro-depots and electric vehicles (scenario 2). The use of parcel shops and parcel lockers for last-mile delivery requires private customers to be willing to walk to a nearby parcel shop (post office) or parcel locker to pick up their parcels. This measure gives private customers a longer time window (about seven days, according to Deutsche Post DHL) to collect their parcels compared to home delivery, which takes only a few minutes to become failed delivery.

It is important to highlight that several factors, some of which are outside the control of the CEP service providers, such as government policy measures, have an impact on how well logistics measures perform. For instance, Narayanan & Antoniou (2021) pointed out that operational factors (such as catchment area, goods type, and delivery density), vehicular factors (such as electric range, purchase price, and technology), infrastructural factors (such as cycling infrastructure and charging stations), workforce, organizational, and policy aspects, all have an impact on the acceptance of e-cargo bikes. However, the exploration of such factors is beyond the scope of this research.

7. Conclusion and Limitations of the Research

7.1. Conclusion

Despite the general assumption 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 concerns about greenhouse gas (GHG) emissions. Therefore, using the agent-based transport simulation MATSim and the integrated logistics behaviour model jsprit, an empirical analysis was conducted to examine the alternative logistics measures available to CEP service providers and the viability of each logistics measure in small- and medium-sized cities.

This research revealed that electric trucks are not cost-effective and efficient as a stand-alone logistics measure in small- and medium-sized cities. It is not cost-effective because electric trucks are more expensive than diesel trucks of the same size and tend to have a lesser payload capacity. This results in more tours, more vehicles required, and more freight mileage. Total transport costs incurred from using electric trucks for the last-mile is 37.8% higher than those of diesel trucks. Nonetheless, electric trucks provide higher environmental benefits than diesel trucks because they emit fewer CO_2 emissions (35.8% reduction) and no CO, HC and NO_X emissions. Furthermore, when electric trucks are coupled with other sustainable logistics measures, they can significantly improve last-mile delivery.

The use of e-cargo bikes in conjunction with micro-depots and electric trucks is a feasible logistics measure. Due to the two-step delivery process, there is a 284.8% increase in freight tours, but the number of vehicles required can be optimised. In comparison to using diesel trucks for last-mile delivery, the mix of e-cargo bikes with electric trucks in conjunction with micro-depots showed reductions of 14.2% in total transport costs even though fixed costs increased, 37.6% in total freight mileage, 84.1% in CO_2 emissions, and 100% in CO, HC and NO_X emissions. However, using e-cargo bikes requires a good scheduling strategy to optimise their daily use and maximise the benefits of the logistics measure.

The use of parcel shops and parcel lockers in combination with electric trucks is also a viable logistics measure. It is observed to be the most cost-effective measure for CEP service providers, with a 31.2% decrease in total transport costs. The number of tours increased by 32.1% compared to the diesel trucks scenario. But the number of vehicles required can be reduced using an optimisation algorithm. Compared to the utilisation of diesel trucks for last-mile delivery, there is a significant reduction of 60.4% in total freight mileage, 80.6% in CO_2 emissions, and 100% in CO, HC and NO_X emissions when parcel shops and parcel lockers coupled with electric trucks are used. This measure also improved road network conditions in terms of average road speed by 5.9%. However, private customers must be willing to accept this measure against home delivery even though it offers more guarantee of successful deliveries because private customers can pick up their parcels anytime.

In general, the three modelled scenarios have less negative environmental impacts compared to the use of diesel trucks because they have zero CO, HC and NO_X emissions, and CO_2 emissions are reduced by at least 35.8%. This shows the environmental benefits of electric vehicles (electric trucks and e-cargo bikes) in comparison to conventional internal combustion vehicles. Observed results are valid for the scenarios modelled. Still, there may be little variations in the results due to the vehicles' specifications and the study area's condition regarding the number of micro-depots, parcel shops and parcel lockers. Nonetheless, for last-mile delivery in small- and medium-sized cities, CEP service providers should consider switching to sustainable logistics measures that are more effective than diesel trucks in terms of operational transportation costs and environmental impacts.

The use of e-cargo bikes with micro-depots and the use of parcel shops and parcel lockers in combination with electric trucks are feasible logistics measures for last-mile delivery in small- and medium-sized cities such as the municipalities in the Aachen city region (Städteregion Aachen). However, the effectiveness of logistics measures is affected by several factors, some of which are beyond the control of the CEP service providers, such as government policy initiatives. Hence, CEP service providers will need to consider these measures when deciding on the best logistics solutions.

7.2. Limitations of the Research

The limitations of this research are as follows:

1. Unavailability of a calibrated network: A calibrated road network allows for evaluating the entire transport system. To the best of my knowledge, there was no available calibrated road network for the study area. Creating a calibrated road network for the study area would have taken considerable time off this research's main focus. Hence, the surrounding traffic effect was integrated using the average congestion level of the study area.

2. The assumption made in section 4.2 (Definition of Key Performance Indicators for Analysis) that the number of vehicles equals the number of tours is inaccurate. Note that a tour refers to the delivery activity of a vehicle, containing several parcels based on its payload capacity, from the distribution centre and back to the distribution centre. Given this definition, the number of tours performed per scenario is correct. However, the average delivery time in scenarios 2 and 3 is about 2 hours per tour. With this, it can be expected that a vehicle in these scenarios can perform more than one tour per day since the average working hours per day is about 8 hours.

3. The major CEP service providers within the study area were modelled as one entity, i.e., a white-label CEP service provider. The research assumed that all distribution centres, parcel shops, parcel lockers and micro-depots belonged to one CEP service provider. This is not the case in reality; however, this research focuses on the benefits of alternative logistics measures to CEP service providers in general. Focus on the different CEP service providers would warrant knowing their share of freight volume and assigning CEP facilities to them. This is beyond the scope of my research. Further research can consider the viability of these logistics measures for last-mile delivery in small- and medium-sized cities with a choice to select from the different CEP service providers.

4. In the scenario of parcel shops and parcel lockers with electric trucks, there was no consideration for the time cost of private customers. In this measure, private customers must go to parcel shops and parcel lockers to pick up their parcels. The time cost of customers using parcel lockers was modelled in the study of Zhang et al. (2018). Although from a CEP service provider's perspective, this is less relevant.

5. This research did not consider the fixed costs, variable costs and personnel costs associated with operating and maintaining the CEP facilities such as micro-depots, parcel shops and parcel lockers.

6. This research did not study the impacts of varying micro-depot numbers on last-mile delivery. However, further studies can be done on this in the context of small- and medium-sized cities.

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