The impacts of Sustainable Concepts in Urban Freight Distribution

A Courier, Express and Parcel Case Study

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at the Professorship of Modelling Spatial Mobility
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A little over half of the current world population are reported to be currently living in urban areas. According to the UN Department of Economic and Social Affairs, this fraction is projected to increase to two-thirds of the world population by 2050 (United Nations, 2018). These increasing economic activities in urban areas do not only have an impact on travel demand for passenger transportation, rather, the impact is felt throughout the entire transport system. Freight transportation is one aspect of the transportation system where the impact of rapid urbanization is also experienced.

The digitalization of the freight demand end, in form of e-commerce, has spawned an exponential growth in the freight transportation industry. BIEK (2019), reports that, in 2018, a total of 3.52 billion shipments were transported in the German courier, express and parcel (CEP) shipment industry. This reported figure translates to a record-high average of about 12 million parcels, delivered to 7 million recipients, per delivery day in Germany. These rising figures are an underlining stimulus for a consideration of the impact of freight transportation activities on the overall transportation system, as well as its effects on the environment.

This research will focus on modelling impacts of sustainable measures in courier, express and package delivery systems, using Berlin as its case study. An agent-based travel demand model will be employed for this study as it is fit for purpose. The use of an agent-based, microscopic transport simulation model is to allow for the generation of finer details in the shipment distribution process. This study will be able to analyse the impacts of implementing these sustainable policies using indicators such as the volume of trips, fossil fuel consumption, fleet size and costs to the service providers.

This research aims to provide answers to the overarching questions:

i.   How does the implementation of policy, logistics and technological measures impact the transportation system, environment, and the operating costs of CEP distribution in urban areas?

Table 1. Timeline of the thesis

	Feb. 2020	March 2020	April 2020	May 2020	June 2020	July 2020
Literature Review	■	■				
Methodology Design		■				
Preliminary Results			■			
Further Analysis & Results				■	■	
First Draft of Writing					■	
Final Draft of Writing						■
Submission						■

For Transportation Systems Master's Thesis:

The student will present intermediate results to the mentors (Nico Kühnel, Prof. Dr.-Ing. Rolf Moeckel and Dr.-Ing Carina Thaller (external - DLR)) in the fifth, tenth, 15th and 20th week.

The student must hold a 20-minute presentation with a subsequent discussion at the most two months after the submission of the thesis. The presentation will be considered in the final grade in cases where the thesis itself cannot be clearly evaluated.

_____
Nico Kühnel

_____
Univ.-Prof. Dr.-Ing. Rolf Moeckel

_____
Student's Signature

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Abstract

A little over half of the current world population are reported to be living in urban areas. This rapid urbanisation stems from an increase in rural to urban migration. Freight transportation is one aspect of the transportation system, where the impact of rapid urbanisation is experienced. The exponential growth of urban areas and increased number of freight trips significantly impacts the quality of urban life negatively. These impacts include traffic congestion, noise pollution, carbon emissions, among others.

This research project examines the viability of implementing sustainable policy, logistical and technological measures for freight transportation in urban areas. An agent-based approach is used to model the impacts of specific sustainable measures in courier, express and parcel delivery systems, using Berlin as its case study.

This research demonstrates that the implementation of policy, logistical and technological measures can significantly reduce freight distance travelled and emission levels. This research could, however, not demonstrate that the implementation of sustainable measures could achieve a reduction in operating costs for logistics service providers in the courier, express and parcel (CEP) industry.

In this study, two sustainable case scenarios are benchmarked against a baseline scenario. The sustainable scenarios recorded at least 4% reduction in total distance travelled while a reduction of at least 25% is recorded in the average distance travelled by each freight vehicle. At least 30% reduction of CO_2 emissions was recorded for the case scenarios modelled. Air pollutant emissions, consisting of CO, PM_{10}, HC and NO_x also recorded a 41% reduction in the sustainable case scenarios. Costs attributed to fuel consumption also recorded a reduction of about 35% while total costs increased by 19% in one of the scenarios.

The improvements recorded in the sustainable case scenarios significantly outweigh the declines. The findings from this study reveal that the implementation of low-emission zones, micro depots, and partial fleet electrification has the potential to produce significant positive impacts on vehicle distance travelled and emission levels.

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1. Introduction

Over 50% of the current world population currently live in urban areas. The UN Department of Economic and Social Affairs projected that this percentage would increase to two-thirds of the world population by 2050 (United Nations, 2018). Besides, rapid urbanisation, coupled with the growing world population, is predicted to increase current world population by 32% in 2050. This rapid urbanisation, resulting from an increase in rural to urban migration, is a response to better economic opportunities in urban areas or lack of economic opportunities in rural areas (United Nations 2018). Growing population, rapid urbanisation and increased economic activities are ingredients for increased transport activities in urban areas. The need to travel in urban areas is intensified by an increase in economic activities of a growing population.

Moreover, travel demand is derived from the need to perform daily activities such as work, school and shopping. This travel demand is usually reflected in the number of trips made in urban areas. These increasing economic activities in urban areas do not only have an impact on travel demand for passenger transportation; instead, the entire transport system feels the impact. Freight transportation, one aspect of the transportation system, also experiences the impact of rapid urbanization. With increased economic activities, comes an increase in the volume of trade, thus increasing the demand for goods transportation. However, freight transportation has dramatically developed over the years, owing to a corresponding growth in urban areas. In a bid to provide improved services, stakeholders in the freight transportation industry have implemented systems that have significantly altered the freight demand structure, leaving freight transport volumes on a steady ascent.

Kauf (2019), elaborates on the changing dynamics in freight transportation, primarily attributed to the introduction of technology and digitalisation of sales services, widely known as "e-commerce". These services provide easier access and a broader reach to a large customer base, as goods can now be ordered easily, by anyone and from anywhere. The digitalization of the freight demand end, in the form of e-commerce, has spawned an exponential growth in the freight transportation industry. BIEK (2019), reports that the German courier, express and parcel (CEP) shipment industry transported a total of 3.52 billion shipments in 2018. This reported figure translates to a record-high average of about 12 million parcels, delivered to 7 million recipients, per delivery day in Germany. These rising figures are an underlining stimulus for consideration of the impact of freight transportation activities on the overall transportation system and the

environment. The total volume of shipments transported for the year 2018 was a 4.9% increase over the total volume transported for the previous year, also the highest year-on-year growth, ever recorded, in the CEP industry. These rising figures are an underlining stimulus for a consideration of the impact of freight transportation activities on the overall transportation system, as well as its effects on the environment.

Moreover, the increase in demand for transportation in urban areas, in developed cities, usually results in a corresponding development of infrastructure and services offered by the transportation system. Cities in developed nations try to match their transport supply with the transport demand generated. This dilemma raises the consideration of sustainable development – defined by United Nations (1987), as a form of development that *"meets the needs of the present without compromising the ability of future generations to meet their own needs."*

1.1. Motivation for the research

While certain key developments in urban areas can be associated with the technological advancements of the transportation system, the adverse effects of these advancements cannot be neglected (Condurat et al. 2017). According to Kauf (2019), the exponential growth of urban areas and increased number of trips significantly impacts the quality of life negatively. These impacts range from traffic congestion to noise pollution, carbon emissions, among others.

Roth et al. (2015), revealed more remarkable statistics that indicate that, over the last decade, there has been a hundred per cent increase in the amount of freight transported worldwide. BIEK (2019) predicted that this rapid growth in global freight transport would to continue as population growth and rapid urbanisation are on a steady rise. Kauf (2019), reiterated this concern, citing the negative impacts of exponential development and increasing traffic flows in urban areas. Pojani & Stead (2015), cited challenges from transport-related activities to include traffic congestion, environmental pollution and energy depletion, among others. Condurat et al. (2017) corroborated Pojani & Stead (2015), referring to the negative impacts of transport-related activities as externalities. These transport externalities consist of energy and fuel consumption, depletion of natural resources and disruption of balance in the ecosystem.

However, there have been concerted efforts, in developed regions, to mitigate the increasing impact of externalities from transport-related activities (Pojani & Stead, 2015). Some of these measures, employed in developed regions, are in a bid to achieve

sustainable urban development. These include, but not limited to, restriction of vehicles in certain parts of urban areas and encouraging the use of non-motorised and eco-friendly vehicles.

This research is borne out of a recognition of negative externalities of freight-related transport activities and the innovative measures that have been developed to mitigate them. In this light, this research project examines logistical, technological and policy measures that promote sustainable freight transportation in urban areas.

1.2. Aim and Objectives

This research project aims to investigate the viability of implementing sustainable policy, logistical and technological measures for freight transportation in urban areas, to mitigate the negative externalities of transport-related activities. This research focuses on modelling the impacts of specific sustainable measures in courier, express and parcel delivery systems, using Berlin as its case study.

This study employs an agent-based transport demand model as it is fit for purpose. The use of an agent-based microscopic model is to allow for the generation of finer details in the shipment distribution process. An agent-based model, as will be demonstrated later in this research, is also capable of considering complex interrelationships and dynamic interactions between different stakeholders in the logistics environment. This study will analyse the impacts of implementing these sustainable policies using indicators such as the volume of trips, fuel consumption, fleet size and costs to the service providers.

1.3. Research Question

This research aims to provide answers to the overarching question:

i. How does the implementation of policy, logistics and technological measures impact the volume of freight trips, emissions, and the operating costs of freight distribution in urban areas?

1.4. Research Procedure

This research project will achieve its objectives using the procedure described in Figure 1.1. In the first chapter, the objectives of the research are outlined, and the research question will be defined. The second chapter will discuss relevant literature as it pertains to the subject matter. The research will proceed to define the study area and define case scenarios that are evaluated. Furthermore, a formulation of the model and description of scenarios will be presented. After that, the results of the simulation are presented and discussed to complete the evaluation of the project results.

Definition of Objectives
- Definition of research question and objectives
- Establishment of the research procedure

Literature Review
- State of the art in Urban Logistics
- Examination of Logistics, Policy and Technological Measures
- Evolution of Urban Freight Transport Modelling

Methodology & Definition of Case Study
- Definition of modelling requirement and process
- Scope of the Study
- Description of Measures to be modelled

Development and Implementation of Model
- Development of Case Scenarios
- Formulation of Model
- Microscopic Modelling of Case Scenarios

Evaluation of Model Output
- Analysis of Results
- Microscopic Modelling of Case Scenarios
- Evaluation of Indicators for Case Scenarios

Figure 1.1 The Research Procedure (Source: Own Diagram)

2. Literature Review

This chapter provides a theoretical framework for the research. Within this framework, relevant terms are defined to provide a background to the scientific approach employed. Furthermore, this chapter also gives an overview of the domain being investigated as well as the methodological approaches used in related studies.

2.1. Definition of Terms: Urban Logistics

In a bid to provide a framework for modern research in urban logistics, Cardenas et al. (2017) analysed several works of scientific literature, from various academic sources. Cardenas et al. pointed out a lack of generally accepted definitions for urban logistics terminologies. Therefore, it is necessary to establish a definition of terms as it relates to this research to achieve consistency in the usage of terms within this study.

Urban Logistics is an umbrella term, comprising of technical, socio-economic and behaviour analyses of stakeholders revolving around the distribution of goods in urban centres. The technical analysis of urban logistics covers the vehicle and goods flow, characteristics of goods and operational or systemic analysis, among others. The socio-economic analysis of urban logistics revolves around decision-making and policy development as well as public perception. Behaviour analysis in urban logistics involves an understanding of the interrelationships and dynamics of the different actors within the urban logistics system. (Cardenas et al. 2017)

A thorough search of the relevant literature presents Cardenas et al. (2017), as the most recent study that attempts to consolidate the functional and geographical elements, as well as the analytical interests, of urban logistics into a typology. By doing this, the authors contribute to a standard framework that would guide the usage of terms for subsequent research in the field of urban logistics.

The authors present three major "domains of Urban logistics": City logistics, Urban goods distribution and Last-mile delivery. The classification of these domains, presented in Figure 2.1 provides a holistic view of the different scales of urban logistics.

- **Concentration of Analysis:**

City Logistics | **Urban goods distribution** | **Last-Mile Delivery**

Public Welfare and Quality of Life | *Sustainable solutions* | *Operational Efficiency*

- **Planning horizon:**

City Logistics | **Urban goods distribution** | **Last-Mile Delivery**

Long- Term Planning | *Mid- Term Planning* | *Shot-Term Planning*

- **End Users of Solutions:**

City Logistics | **Urban goods distribution** | **Last-Mile Delivery**

Stakeholders Policy Makers General Public | *Set of Service providers, supply chain and resource managers* | *Service Providers*

Figure 2.1 Distinction between scales of Urban Logistics (Source: Own diagram based on Cardenas et al. 2017)

2.1.1. City logistics

Cardenas et al. (2017), depicted city logistics as the top-level domain of urban logistics. This domain is depicted as the largest scale in urban logistics because the analysis here is geared towards the interrelationship between public perception, administrative policies, and the logistics system. City logistics analyses do not only suggest solutions to comply with policies, but they also include the process leading to the formulation of logistics policies. However, the increasingly complex and dynamic relationship between

actors in the logistics system is also considered in city logistics. Modelling approaches in this domain also favour multi-agent-systems, owing to its capabilities of modelling complex environments, revealing fine details of the interdependencies of stakeholder behaviours. Another characteristic of research under this domain is a standard orientation towards long-term planning measures.

2.1.2. Urban goods distribution

This domain of urban goods distribution focuses on operational analyses, specifically suggesting more efficient options for delivering goods into and within urban areas. Many at times, research in this domain proffer solutions to comply with administrative policies, pre-emptive or in-effect. Cardenas et al. (2017) suggested that urban goods distribution studies may also investigate measures to limit emissions on the urban scale. The scope of this domain is lesser than the "city logistics" domain. Cardenas et al. (2017) highlighted that the distinguishing factor is that the urban goods distribution domain is not concerned with the process of formulating policies, unlike city logistics.

2.1.3. Last-mile delivery and collection

The term "last-mile" is a commonly used term in transportation to depict the final leg of a journey. However, depending on the scope of the study, the definition of a "last-mile" journey might vary. In most cases, the transport means for last-mile journeys are usually smaller in scale, compared to the entire journey. The reason is that the transport volume decreases as traffic approaches the last mile and also, there are potential diseconomies of scale associated with last-mile journeys. (de Grange et al. 2018)

In urban logistics, however, last-mile delivery depicts the final journey of goods in the delivery cycle. The last-mile is the journey from the last node of handling, in the logistics set-up, to the point of delivery (Cardenas et al. 2017). Logistics providers tend to optimize last-mile delivery to increase efficiency and avoid rising costs.

Table 2.1 Typology of Urban logistics. (Source: Cardenas et al. 2017)

Characteristics	City Logistics	Urban Goods Distribution	Last-mile Delivery and Collection
Research methodologies	Survey Agent-based simulation Multi-criteria analysis	Transport simulation Mathematical modelling Agent-based simulation	Mathematical modelling Operations research Routing simulation
Network typology	Full ecosystem of urban logistics Information flows focused	Freight transport system Terminals and consolidation centres Multimodal transport	Deliveries Multi-node networks Loading and unloading spaces
Type of variables	Towards qualitative	Neutral	Towards quantitative
Performance measurements	Quality of life Competitiveness Outcomes from regularization	Traffic congestion reduction Emissions Financial performance Number of vehicles	Distance Time Load factor Operational costs
Research subjects	Stakeholder relationships Sustainability Systemic approach challenges Collaboration Decision-making process Land use	Data collection process Urban distribution centres Freight transport infrastructure Public policy performance Emissions	Routing Distance reduction Optimization Alternative vehicles
Planning horizon	Towards long-term decisions	Towards mid-term decisions	Towards operational decisions
End-users of Solutions	Stakeholders and policymakers	Set of firms, their supply chains, and resource and infrastructure managers	Firm and supply chains

Following a distinction between the three domains of urban logistics, summarized in Table 2.1, it is necessary to specify which of these domains is covered in this research. It has been earlier established, in 1.2, that this research focuses on modelling specific sustainable solutions that could potentially mitigate negative externalities of freight transportation. This research considers that sustainable solutions could be an adaptive measure to administrative policies; it does not, however, consider the process of formulating these policies. This is a unique feature of investigations in urban freight distribution, described in 2.1.2. For clarity, this research can be characterized as one within the urban freight distribution domain, owing to intersections between the focus of this research and attributes discussed in 2.1.2.

2.2. Overview of the Courier Express and Parcel Industry

Freight transportation is a large domain within the transportation field, consisting of different sectors, providing tailored services to specific industries, at varying scales. This research project is concerned with freight transportation at the urban scale concerning courier, express and parcel (CEP) services. This sub-chapter examines the characteristics of the CEP industry, to provide a contextual background for the research case study, which is explored later in Case Study of this text.

As established already, the CEP industry is a specific segment of the freight transportation domain. The characteristics of CEP traffic is presented in Table 2.2, as it relates to the transport operations, consumer base and services provided.

Table 2.2 Characteristics of CEP Traffic (Source: Own representation according to Thaller 2018)

Characteristics	CEP Traffic
Transport Objects	Small goods
Shipment sizes	2kg - 31.5 kg
Loading units	Package units (PE), pallets
Functional scale	Local, regional, long-distance transport
Mode of transport	Road, Air
Means of transport	Cargo-bikes, trucks with 3,5 - 7.5 t gross vehicle weight, permitted for local traffic (pre- and on-carriage); Trucks with 7.5 - 40 t gross vehicle weight or aircraft, permitted for long-distance traffic in the main run
Transport network structures	Direct transport network, hub and spoke network
Transport concept	Direct delivery, consolidated goods sweep
Transport chain	Pre-, main- and post-carriage
Customer industries	Business-to-Business (B2B), Business-to-Consumer(B2C), Consumer-to-Consumer (C2C) Industry

CEP service providers have a variety of services, targeted at Business-to-Business (B2B), Business-to-Consumer (B2C) and Consumer-to-Consumer (C2C) clienteles (Thaller 2018). The author interpreted Business-to-Business (B2B) clientele to include companies who send small-sized shipments in the industry and services sector. The B2B clientele is part of the commercial sector using CEP services, which also includes Business-to-customer (B2C) clientele delivering shipments from mall orders and direct sales. Private individuals who send parcels constitute the consumer-to-consumer(C2C) clientele. A summary of sub-services within the CEP industry is presented in Table 2.3.

Table 2.3 Distinction of CEP services (Source: Thaller 2018)

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	Shipment weight up to 1.5 kg	Shipment weight up to 31.5 kg	Shipment weight up to 31.5 kg
Means of transport	Cargo bikes and trucks with 3.5 to 7.5 t permissible gross weight	Cargo bikes, trucks with 3,5 up to 7.5 t permissible gross weight for local transport; trucks with 7.5 to 40 t permissible gross weight or aircraft for long-distance transport	Cargo bikes, trucks with 3,5 up to 7.5 t permissible gross weight for local transport; trucks with 7.5 to 40 t permissible gross weight or aircraft for long-distance transport
Transport network structures/ transport concept	Direct delivery without fixed networks and lines	Hub and spoke network with groupage traffic	National and international hub and spoke network with groupage traffic
Functional scale	Local, regional transport	Local, regional, long-distance transport	Local, regional, long-distance transport
Field of application	Local, regional, and national area of operation	National and international field of application	National and international field of application
Transportation time	Delivery on the same day or by individual agreement	Fast, day- and time-exact delivery as well as home delivery door-to-door service (same day, night, next day and overnight delivery)	National delivery time: 1 - 2 days; international delivery time: 1 week
Service level	Personal and direct accompaniment of the consignment	Carriage 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 international large companies	Large international companies

2.2.1. Impacts of urban freight transport operations

Advancements in the courier, express and package (CEP) sector has resulted in an increasing demand for small-sized goods in urban areas. This increased demand translates to an increase in the frequency of small-scale shipments and deliveries. Thaller (2018) suggests that these "highly-frequented" small-scale deliveries lead to a significant increase in demand for urban freight transportation.

Moreover, Thaller (2018) opines that commercial vehicles used in urban freight transport have an impact on the emissions and noise level in the environment, as well as on traffic flows due to frequent stops by these commercial vehicles for delivery. This conforms with Browne et al.'s (2012) view on the environmental impacts of urban freight transportation which is presented in Figure 2.2.
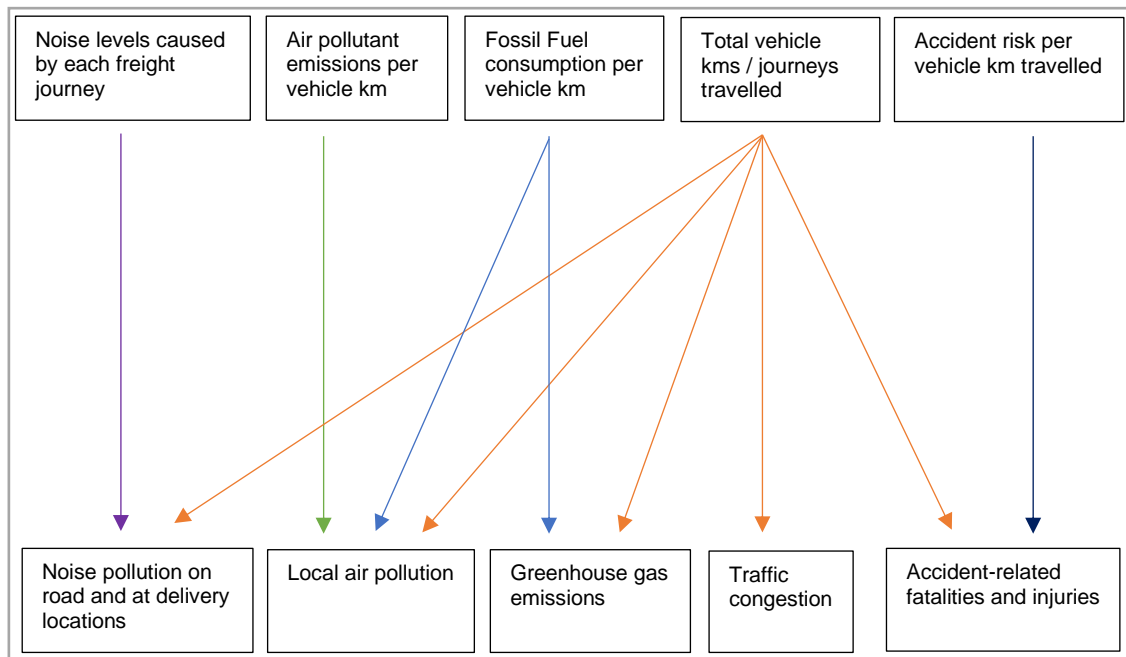
Figure 2.2 Negative Impacts of urban freight transport operations. (Source: Browne et al. 2012)

Following a description of urban logistics in 2.1 and an overview of CEP services in 2.2, it is vital to explore the efforts that have made by various cities to mitigate the negative externalities of urban freight transport operations. The next sub-chapter discusses these efforts.

2.3. Sustainable Measures in Urban Freight Transportation

Unlike passenger transportation where there is an increasing clamour for a reduction in trips, it would be unrealistic to propose limited goods flows in time and space as the growth of economies is usually associated with trade volume. However, the increasing avenues for goods to flow in time and space have impacted the volume of passenger travel for specific purposes. An excellent example of this is the e-commerce/home delivery versus market trips dichotomy.

There are schools of thought that give credence to theories of neighbourhood accessibility and transit-oriented development. The idea that when activities, which are regularly performed, are situated close to areas of habitation, people are less likely to travel. This theory relies on the school of thought that transportation is a derived demand, required for performing some form of activity. Hence, situating these activities near the inhabitants would significantly reduce the need for travel. The logistics perspective of this theory hints that bringing the goods to the consumer could reduce or eliminate the need for the customer to travel.

Since it is established that freight transportation cannot be treated the same way as passenger transportation, it becomes imperative to seek novel ways and innovative ideas to achieve a sustainable transportation system. This sub-chapter examines three categories of measures that have been developed to enhance the sustainability of urban freight transportation. The next sub-chapters explain the three categories of measures, transport policy, logistical and technological measures.

2.3.1. Transport Policy Measures

In a bid to mitigate the negative impacts of logistics operations, policymakers develop policies and regulations. These policies are in the best interest of the city residents and aim to improve the quality of life. Measures are usually tailored towards an objective or a set of objectives. The scope of policies developed could range from large-scale (international) to small-scale (local municipalities). However, this sub-chapter will examine policy measures developed by authorities at the urban scale.

While the policies reviewed in this part of the study are not exhaustive, the aim is to explore some common initiatives from different cities tackling the same problem. The next sub-chapters explore the concept of low-emission zones and urban consolidation centres.

- *Low-emission zones:* Policymakers in several European countries have implemented low-emission zones (LEZ) to restrict vehicles with high-emission ratings from entering their cities. Amundsen & Sundvor (2018) described low emission zones as an initiative to reduce particulate matter and NO_2 emissions in cities. Amundsen & Sundvor cited that diesel-powered engines are more affected by the measure, as the restrictions are strict on them compared to petrol-powered engines. Amundsen & Sundvor explained that if LEZs are to be implemented in more than one city in a country, a national framework is required for consistency. However, each city still has the autonomy of implementation and determining the location of the LEZ. Amundsen & Sundvor cited examples of Germany and France whose national framework involves the use of stickers to signify rating of vehicles. Table 2.4 shows the present and future European emission standards for vehicles based on their first date of registration (Green-Zones GmbH 2019).

Table 2.4 Environmental Badge Classification (Source: Green-Zones GmbH 2019)

Eco badge Class	Two-, three- and light motorized four-wheelers	Cars		Light Utility Vehicles < 3,5 t		Trucks, Busses	
4 GR UN 2004		Hydrogen – and Electric Vehicles, Gas powered vehicles, Hybrid Vehicles					

		First registration date or Euro standard					
Eco badge Class	Two-, three- and light motorized four-wheelers	Cars, Campers < 2,8 t		Light Utility Vehicles < 3,5 t		Trucks, Busses Campers > 2,8 t	
		Diesel	Petrol	Diesel	Petrol	Diesel	Petrol
4 GR UN 2004	no badge necessary and possible	Euro 6 starting 01.09.2015	Euro 6 starting 01.09.2015	Euro 6 starting 01.09.2015	Euro 6 starting 01.09.2015	EURO 6 starting 01.01.2014	EURO 6 starting 01.01.2014
4 GR UN 2004	no badge necessary and possible	EURO 5 from 01.01.2011 until 31.08.2015	EURO 5 from 01.01.2011 until 31.08.2015	EURO 5 from 01.09.2010 until 31.08.2015	EURO 5 from 01.09.2010 until 31.08.2015	EURO 5 from 01.10.2009 until 31.12.2013	EURO 5 from 01.10.2009 until 31.12.2013
4 GR UN 2004	no badge necessary and possible	EURO 4 from 01.01.2006 until 31.12.2010	EURO 1-4 from 01.01.1993 until 31.12.2010	EURO 4 from 01.01.2006 until 31.08.2010	EURO 1-4 from 01.10.1993 until 31.08.2010	EURO 4 from 01.10.2006 until 30.09.2009	EURO 1-4 from 01.10.1993 until 30.09.2009
3 GE L8 2003	no badge necessary and possible	EURO 3 from 01.01.2001 until 31.12.2005	-	EURO 3 from 01.01.2001 until 31.12.2005	-	EURO 3 from 01.10.2001 until 30.09.2006	-
2 R0 T 2002	no badge necessary and possible	EURO 2 from 01.01.1997 until 31.12.2000	-	EURO 2 from 01.10.1997 until 31.12.2000	-	EURO 2 from 01.10.1997 until 30.09.2001	-
No Eco badge	no badge necessary and possible	EURO 0-1 until 31.12.1996	without catalyst	EURO 0-1 until 30.09.1996	without catalyst	EURO 0-1 until 30.09.1996	without catalyst

In the Netherlands, Browne et al. (2012) noted that cities in the Netherlands, who implemented LEZs in 2006, have placed access restrictions on vehicles below the Euro IV engine standard. Browne et al. mentioned that even though the LEZ implementation has resulted in some environmental quality improvements, the benefits are not as high as anticipated. Browne et al. associate these low gains to the fact that new vehicles have not necessarily been as clean as purported. Besides, Amundsen & Sundvor (2018) also pointed out that challenges with evaluation methodologies make it difficult to ascertain the extent of environmental effects resulting from LEZs adequately.

- *Urban Consolidation centres:* The concept of consolidation centres have been tested in several cities, with each city having a different approach to their measure. This initiative involves the gathering of shipments, intended for a city, at a central consolidation centre. This consolidation centre is usually designed to handle the sorting of goods for redistribution to different delivery zones within the city. Browne et al. (2012) described an experimental use of a consolidation centre in London, United Kingdom. Browne et al. explained how the city authorities supported the use of a micro-consolidation centre, in 2009, for the delivery of office supplies to customers within the city of London. For the trial period, the city of London employed eco-friendly vehicles for distributing shipments from the micro consolidation centre to customer delivery locations. Browne et al. highlighted that these vehicles were electric vehicles and electrically assisted tricycles, powered with electricity generated from renewable sources. Hence, zero-emissions generated. The results of the trial revealed a 20% reduction in distance travelled per parcel between the main depot and the points of delivery.

  Browne et al. (2012) described the implementation of a consolidation centre in Motomachi street in Yokohama, Japan. Being a commercial district with several shopping stores, the street experienced a high volume of car through-traffic, which negatively affected the environmental quality of the area. Stakeholders which included city authorities, along with shop owners, decided to implement a collaborative delivery system using a consolidation centre. Browne et al. reported that about 20 carriers were involved in this cooperative delivery system. Located one kilometre from Motomachi street, the consolidation centre was equipped with low-emission vehicles to distribute shipments to their delivery locations.

2.3.2. Logistical measures

Carriers have been actively involved in the development of measures to improve the sustainability of their operations. Some initiatives developed by carriers in selected cities are discussed below.

- *Distribution Networks Collaboration*: This initiative involves the consolidation of shipments from different shippers and then exchanging these shipments between carriers on a collaborative network, resulting in a higher drop density and load factor. The aim here is to avoid multiple carriers delivering to one zone within the urban area (Quak 2012). This way, each carrier handles all deliveries to a specific zone on the distribution network. Quak (2012) illuminated on the fine details of this collaboration, citing large carriers, with extensive network coverage, can implement this initiative single-handedly. On the other hand, carriers without central hubs must coordinate direct exchanges of shipments.

  Quak (2012) mentioned "TransMission", the largest of this collaboration between independent distributors in the Netherlands and Belgium, having a total of 16 distribution firms. To allow each firm to operate in one region, the collaborative partners divided the Netherlands and Belgium into operating regions. The Netherlands was divided into 13 distribution regions, using one of these regions as a central depot. The modus operandi entails the following: goods intended for the collaborative network are transferred from the regions to the central depot. The goods are exchanged and sorted overnight for each partner to pick up and deliver to their respective regions. Quak (2012) also mentioned that, for consistency reasons, the partners use the same software and barcodes for shipment tracking and tracing. Quak (2012) reported that shipment from the collaborative network accounts for 87% of the total shipments handled by the Amsterdam region partner. Impressively, this has resulted in savings of four-times less the number of trucks required for urban freight transport in Amsterdam.

  Other positive results, from more examples of this collaborative network initiative, indicate a lower number of vehicles required, increased vehicle capacity utilization, lesser vehicle kilometres travelled and as a result, lower emissions produced. On the negatives of this initiative, Quak (2012) explained that due to time window restrictions, it is not always possible to deliver all shipments as the volume of deliveries is higher.

- *Decoupling at the border of the city centre:* Quak (2012) examined another logistic measure developed by carriers to achieve the objective of a sustainable urban freight

transport system. Quak (2012) described two forms of this measure. The vehicular decoupling – a system of trucking whereby heavy-duty long-distance trucks can have their trailers decoupled at the border of the city centre and then lighter-duty vehicles can make the inner trip to city centres. This measure is different from decoupling at city distribution centres as there is no transfer of shipments from one truck to another and as such, handling is not required. The study mentioned "Ecocombis" and "swap bodies" - two systems utilized by carriers in the Netherlands. The Ecocombis are unique vehicles that allow coupling of two "city trailers" to one truck. The author reported that these Ecocombis are only permitted on highways and secondary roads. At the border of the city, one trailer can be decoupled and then the other trailer can be driven to the city for delivery. The decoupled trailer can be coupled to another truck for delivery in the city. It is also possible for the first truck to return to the decoupling location to pick up the second trailer for delivery. Positive results highlighted by the author include savings on fuel consumption, efficiency improvements and reduced emissions. In this study, Quak (2012) also mentioned a modular system where shipments are packaged in freight box, to be transported by big freight vehicles which have a capacity for three boxes. These boxes are then transferred to delivery vans, having a capacity for only one box, for onward distribution to the city centre (Quak 2012).

- *Parcel stations and parcel shops:* Generally, home delivery is the most common delivery concept and has the highest acceptance among recipients, according to Bogdanski (2015). With the development of innovative delivery options by logistics service providers, online shoppers can now select the mode of delivery for their parcels. According to DHL (2020), there are at least 4,500 parcel stations in Germany. Parcel stations are automated parcel pick-up centres, in the form of booths, where customers can pick up parcels without time restrictions. These parcel stations are self-service, requiring no human contact. Parcel shops, on the other hand, are partner-shops who provide parcel pick-up and drop-off services as a secondary service to their primary businesses. Logistics service providers partner with various businesses to achieve a good parcel delivery network. Although there are parcel shops whose primary business is to handle parcels, many at times, parcel shops extend parcel handling as a secondary service.

  In a 2017 survey, carried out by PWC (2018), a significant proportion of online shoppers in Germany revealed that they preferred home delivery to other delivery options. Out of a thousand online shoppers surveyed, only about 15% do not order

their parcels for delivery to their homes. However, the PWC (2018) study revealed that customers are much more open to other delivery options. The report highlighted that 50% of online shoppers would be prepared in principle to pick up their parcel at a parcel shop or a parcel station themselves if delivery to that location were standard. However, to these customers, these options are not yet attractive enough. For instance, PWC (2018) report showed that 23% of the customers favour a better network of parcel shops and parcel stations, while 16% give preference to better opening hours and accessibility. PWC (2018) cited the potential for parcel services to make delivery options more efficient if they have a corresponding demand. PWC (2018) recommended that online shoppers would have to be given a transparent display of the options (parcel shop vs home delivery). Logistics services would also have to provide the associated prices for each delivery option during the ordering process. However, this requires closer coordination between the parcel services and their customers, the retailers, in order to increase transparency and the number of delivery options for the consumer (PWC 2018).

- *Micro-Hubs*: Micro-hubs are innovative logistics concepts initiated in recent years, to cope with the increased delivery and reverse logistics trips in urban areas. IHK (2019) described micro-hubs as transhipment locations, used as intermediate storage of goods and parcels in densely populated areas. IHK (2019) added that micro-hubs are the starting and endpoint for urban and resource-friendly customer-oriented delivery or collection. Necessarily, micro-hubs are mini depots used for temporarily storing parcels, in cities, before onward delivery to customers. Decentralized micro-hubs can supplement parcel shops and parcel stations in conjunction with low-emission solutions. Eco-friendly concepts such as electric vans, cargo bikes or crowd delivery solutions are better suited to meet the demand for fast, flexible, and environmentally friendly delivery options. Since real estate is expensive and scarce, especially in urban areas, joint use by several parcel services in the sense of a sharing model is an economically viable and sustainable option. PWC (2018) cited an example of five significant logistics service providers who implemented the sharing of a micro-hub in Berlin, Germany, as part of a pilot project. These service providers distribute parcels from the shared micro-hub with e-truck bicycles. Moreover, the implementation of micro-hubs makes it easier to handle fluctuating demand and to adapt to local conditions.

2.3.3. Technological Measures

With the debate among stakeholders, regarding how much effort should be put into developing sustainable initiatives for urban freight transport, this section highlights technological measures that carriers have implemented so far.

- *Vehicle Engine Design*: Following the introduction of low-emission zones and environmentally protected zones as an environmental regulatory measure in European cities, cleaner vehicles are sourced for urban freight distribution. Quak (2012) argued that diesel trucks account for most of the vehicles used for urban freight transport. This is still true in 2020. However, Quak (2012) reviewed debated and already implemented alternatives to diesel fuel. One of the alternative fuel sources discussed in the article is the use of compressed natural gas (CNG). Quak (2012) described CNG as a cleaner source of fuel compared to emission levels significantly lower than diesel. The author also pointed out barriers to the use of CNG trucks, highlighting the 5-10% premium on the cost of CNG trucks compared to diesel. The largest supermarket chain in the Netherlands, Albert Heijn, uses these CNG trucks to transport decoupled trailers from decoupling locations to the city centre.

  Electric vehicles are also often mentioned as an alternative drivetrain to diesel vehicles commonly used in urban freight transportation. Quak (2012) argued that although electric vehicles do not produce emissions from driving, their emission footprint can be traced to the source of electricity for charging. Quak cited an example of an implementation of electric vehicles for urban freight distribution - Cargohopper – a combination of logistics and technological measures. Cargohopper is an electric delivery vehicle with trailers (Bestfact, 2015). It is an initiative by the collaborative network partner operating in the city of Utrecht. The Cargohopper is used for last-mile deliveries. Picking up shipments from the Hoek distribution centre outside Utrecht and delivering to customers and businesses in the centre. The Cargohopper comprises of a 16-metre long but narrow multi-trailer. Some authors also refer to Cargohopper as a road train (Browne et al. 2012, Quak 2012). The Cargohopper is a zero-emissions vehicle as it is powered by three solar panels, mounted atop the trailers (Bestfact 2015). Positives from the Cargohopper initiative include reduced emissions, flexible deliveries, and reduced traffic congestion. However, the vehicle has several technical limitations (in term of cargo, maximum speed and maximum range) and is best suited to low-speed and short-distance operations (Bestfact 2015). Furthermore, Quak (2012) pointed out the high costs of purchase as the reason behind the slow adoption of electric vehicles for urban logistics. It remains to be seen how advanced

technological development in vehicle manufacturing would drive down the cost of batteries which accounts for a significant percentage of the cost of electric vehicle production.

- *Noise reduction:* In a bid to make deliveries in cities quieter, the project PIEK was born in the Netherlands. In 2004, the PIEK certification was established to certify vehicles operating below a threshold of 60dB(A). This threshold allows for night-time deliveries without noise disturbances (Quak 2012). Several other European countries have adopted this PIEK standard, including France, Germany, Belgium, and the United Kingdom. The homepage of PIEK International describes the certification process. The process requires that loading and unloading functions be carried out on the concerned vehicle while a sound measurement is made 7.5 meters away from the vehicle. The vehicle qualifies for the PIEK certificate if the sound measurement stays below the 60db(A) threshold. Quak (2012) is of the view that carriers in the Netherlands have embraced operating with PIEK certified vehicles as it allows them to perform out-hours deliveries bereft of noise disturbance to the public. Performing out-hour deliveries also implies a reduction in the contribution of urban freight to peak-hour traffic congestion. Quak (2012)highlighted substantial cost savings, reduction in vehicle kilometres as well as emissions reduction.

- *Intelligent Logistics Systems:* Telematic solutions discussed by Quak (2012) entail four resource enhancements to improve the efficiency of urban logistics. The author discussed an intelligent logistics planning system, consisting of four tools, to assist carriers with route planning and operational optimization, taking into consideration constraints such as time windows and access restrictions. This logistics system comprises of a pre-trip planner, a dynamic navigator, a last-mile tracking device and static and dynamic map attributes.

  The "pre-trip planner" is a tool allowing carriers to efficiently plan their routes while considering delivery constraints and real-time traffic information. The dynamic navigator uses advance map technologies to dynamically process traffic information as well as changes on the route. The "last-mile tracking" tool uses advanced vehicle GPS-tracking systems to monitor vehicle position during the last-mile trip to the customer and communicate estimated time of delivery to the customer. The last tool, as described by Quak (2012), aims to provide static map attributes that process information about physical attributes on the planned route as well as dynamic maps that process real-time changing information. The author explained that these map attributes would be specially tailored to a logistics operation use-case.

2.4. Urban Freight Transport Models

Transport models are an essential component of decision-making processes in transport planning (Salanova et al. 2014). In addition to providing a compressed representation of larger scenarios, transport models also provide a platform for simulation and assessment of measures to be introduced into the transport system. The effects of these measures can be evaluated in a virtual setting, and underlying considerations can be identified before implementation in a real-world setting.

However, Thaller et al. (2016) point out the limited research literature on freight transport modelling compared to passenger transport modelling. Thaller et al. (2016) attribute this lack of a standard freight modelling framework to the complexity of stakeholders' behaviours within the urban logistics system. In the absence of a standard framework, Thaller et al. (2016) opine that limitations, to the application, development and advancement of freight transport models, will continue to exist.

The urban logistics system can be likened to a black box where there is limited knowledge of the motivation behind the behaviour of stakeholders. The bulk of activities within the system are carried out by private establishments, and the details of these activities are declared as sensitive business information. Hence, the limited access to data about the intricacies of this system makes it challenging for researchers, putting a constraint on the pace of advancements in developing freight transport models.

This part of this study takes a closer look at the development of freight transport modelling over the years, the variations in modelling paradigms and the state-of-the-art in the field. Approaches and modelling strategies are also discussed to overcome the challenges of limited data of the urban logistics system. Furthermore, a distinction between macroscopic and microscopic modelling is also made, as it pertains to freight transport modelling.

2.4.1. Typology of freight transport models

Thaller et al. (2016) developed a typology for the different characteristics of freight demand models. The authors intended to generate higher information for each type and avoid subordinate relations as well as having types without attributes. Hence, the authors explored the suitability of a typology as opposed to a classification methodology. A thorough search of the relevant literature yielded Thaller et al. (2016), as the most recent study that attempts to create a standard typology for characterizing freight transport models. Thaller et al. (2016), developed this typology and Thaller (2018) further

elaborated on it. The following segment discusses the characterization of freight demand models.

- _Level of Aggregation_: The level of aggregation refers to the granularity of the input data or observations for a model. Thaller et al. (2016) identified two aggregation levels in modelling, aggregated and disaggregated. Ben-Akiva & de Jong (2013) characterized disaggregate models as "models using observations at the level of a traveller, a travelling group, a business establishment or a shipment". Thaller (2018) agreed with this definition, pointing out that disaggregate models focus on the behaviour of individual actors within a system. Agent-based models are a form of disaggregate models. In agent-based models, Thaller (2018) explained that each agent in a multi-agent system is regarded as an individual actor, and detailed analysis can be generated for each agent in the system.

  On the other hand, aggregate models are characterized by their consolidation of observations. Explaining the modus operandi for aggregated models, Thaller (2018) highlighted the division of the study area into traffic attracting zones with each zone generating transport demand. The transport demand for each traffic attracting zone is known as an aggregated transport demand as analysis can only be made for each zone in an aggregated format. For aggregated models, Thaller (2018) further cited the need for zonal structural data and data on transport behaviour at the zonal level. The scale of data required for aggregated models could range from city level to international level.

  Ben-Akiva & de Jong (2013) favoured disaggregation models, compared to aggregation models, highlighting the absence of aggregating bias that could result from aggregation. With aggregated models, there is no possibility of having a differentiated evaluation of the effect of specific measures on individual actors, unlike disaggregated models. However, Ben-Akiva & de Jong (2013) mentioned that there are certain situations where an aggregated model fits better. Furthermore, Thaller (2018) mentions that all aggregated models are macroscopic while disaggregated models are not always microscopic as the data from disaggregated models could also refer to the normal behaviour of a behaviourally homogeneous or similar group.

- _Scale of analysis_**:** The scale of analysis also refers to the degree of detail. Here, Thaller et al. (2016) made a subdivision of transport models into macro-, micro-, and mesoscopic models. **Macroscopic** models map behaviourally-homogeneous or

similar groups based on aggregated data and cannot describe the behaviour of the individual actor. Thaller (2018) mentioned that these models focus on transport flows, mapped on the links connecting the nodes of the infrastructure network. However, Thaller (2018) pointed out that macroscopic models can be based on aggregated and disaggregated data.

In contrast, Thaller et al. (2016) explained that ***microscopic*** models could evaluate the behaviour of individual actors. They can do this by calculating the transport demand of the overall system from the activities of the individual actors whose behaviour is the subject of the study. These models are based on disaggregated data sets. However, Thaller (2018) mentioned that, if disaggregated data sets are not available, they are generated from aggregated data. Due to their high granularity, microscopic models are conventional in evaluations that require a high temporally and spatially detailed degree of resolution.

There are also ***mesoscopic*** models that use macro- and microscopic approaches in combination. Thaller et al. (2016) summarized the scale of analysis, stating that macroscopic models depict transport flows, while microscopic models depict individual agents or actors and mesoscopic models analyse groups.

- *Spatial Resolution*: The spatial resolution level is determined based on the study area. A distinction can be made between international, national, regional, urban, and local models.

- *Modelling Objective*: This refers to the model object or measurement parameter. Thaller (2018) reveals that the modelling objective can be either transport flows or individual trips. Hybrid models consider both flows and trips.

  As explained by Thaller et al. (2016), **flow-based models** focus on the traffic generated by the need to perform economic activities, situated in different traffic zones. Based on the interactions between the traffic zones, the transport demand is transformed into transport flows and presented as loads on the infrastructure network. This approach is mainly used to map the transport volume and the modal split between the different modes of transport. Thaller (2018) highlighted that these models are mainly used for large-scale research areas (e.g. at national and international level). The size of the traffic zones is adapted to the size of the study area. Thaller et al. (2016) also cited that the data sets for flow-based models are statistical relationships between transport volume and structural indicators of individual traffic zones.

For **trip-based models**, Thaller (2018) explained that the transport demand is generated based on structural characteristics of the actors considered. Thaller (2018) expounded on this, stating that the modelling includes vehicle-related characteristic values for the generation of the individual trips of a vehicle in the study area. Trip-based models serve to map spatially and temporally differentiated vehicle movements. Transport demand in these models is usually differentiated according to means of transport distribution and vehicle type. Thaller (2018) explained that, since the trip-related models directly generate the transport demand, they do not require explicit modelling of the modal split. The focus here is more on the consideration of a transport mode (e.g. road) in smaller investigation areas, especially in regional and urban areas.

Hybrid models consider both modelling objectives, transport flows and individual trips. Based on the transport flows, they generate individual journeys. Thaller (2018) described these approaches as primarily microscopic models that represent the decision-making processes of different actors in the system.

- *Time horizon*: For transport models, the time horizon is defined differently. Thaller (2018) made a time-horizon distinction of freight transport models into short, medium, and long-term periods. Short-term horizons reflect the day-to-day business or day-based activities of actors in the system. The time is measured in standard units of measurement of time, seconds, minutes, hours or days. Thaller (2018) associated medium-term periods in transport planning with a legislative period in politics which corresponds to 4 years. Long-term periods, defined by Thaller (2018), are time horizons of 10 to 15 years. For long-term periods, Thaller (2018) cited that planning instruments are usually drawn up for these periods in transport planning. These are planning periods for the implementation of measures. Figure 2 summarized the characteristics of transport models described by Thaller (2018).

Level of Aggregation	Scale of Analysis	Spatial Resolution	Modelling Objective	Time Horizon
• Aggregated • Disaggregated	• Macroscopic • Microscopic • Mesoscopic	• International • National • Regional • Urban • Local	• Flow-based • Trip-based • Hybrid	• Short-Term – Tactical • Medium-Term – Operational • Long-Term – Strategic

Figure 2.3 Characteristics of transport models (Source: Own diagram based on Thaller 2018)

2.4.2.   Methodologies used in Freight Transport Modelling

Freight transport demand models combine a variety of standard methodologies theories and concepts. The approach and application of these methodologies vary from model to model. Thaller et al. (2016) made a distinction between these methods and concepts by categorizing them into six classes. This categorization includes statistical analyses, statistical simulations, distribution methods, optimization, equilibriums, and temporal simulations. In Table 2.5, the categorized modelling methods are presented, alongside use cases for their application as described by Thaller et al. (2016).

Table 2.5 Modelling methods for freight transport demand modelling (Source: Thaller et al. 2016)

Modelling methods	Definition	Subcategories	Application use cases
Statistical analytical methods	Evaluation of empirically collected data with statistical methods	Univariate procedures: fact acquisition, generation of key values	Arithmetic mean: e.g. trip generation rates per employee Distribution: e.g. empirical distribution of distances
		Multivariate procedures: Relations between variables	Aggregated and disaggregated multivariate regression Discrete choice models Cluster analysis Classification trees Variance analysis Data Mining Factor analysis
Statistical Simulation	Creation of an artificial population considering assumptions, knowing that the detailed structured may not be verifiable	Monte Carlo Simulation	Creation of artificial company populations Creation of tours using a random generator
Distribution methods	Column and row totals of a matrix are split, or a total is split into subsets (generally this problem is under-defined)	Entropy maximization, Disaggregation	Derivation of a matrix of flows based on row/column totals Derivation of detailed intersectoral relations based on aggregate IO-flows
Optimization	Formulating a mathematical optimization problem to describe the choices of individual actors	Convex/linear/integer/ nonlinear optimization Exact and heuristic optimization	Route search in diverse models Route planning Lot size models based on Total Logistics Cost Minimization

Modelling methods	Definition	Subcategories	Application use cases
Equilibria	Search for equilibria in markets and transport networks for a comparative analysis	Perfect competition Nash equilibrium Monopolistic competition models	Traffic flow equilibria in diverse models SCGE models (monopolistic competition)
Temporal simulation	Imitation of a system over time (Hartmann 1996) Objectives: Finding equilibria or study in the course of time	Microscopic or macroscopic simulation	Simulation of traffic flows Multi-agent Simulation System Dynamics

2.4.3.   State of the Art in Freight Transport Modelling

This sub-chapter discusses some of the research efforts that have been put forward in a bid to advance modelling approaches in freight transport modelling. A description of models developed in freight transport research and their approaches are examined. Afterwards, attributes pertaining to the typology described in 2.4.1 and the methodologies explained in 2.4.2 are outlined for each of the models discussed below.

i.   **GoodTrip Model**: Developed by Boerkamps et al. (2000), the "good-trip" model is a commodity-based, demand-driven freight flows model that integrates supply chains into its computation. The framework of the model involves the connection of distribution channels to various activities within the logistics system. The model has been developed to be flexible in its computations and, as such, can allow combined usage of empirical data, behaviour models as well as scenario-type assumptions. The model estimates goods flow and simulates vehicle tours to generate transport demand. Activity types are used to represent nodes in the supply chain. The generated consumer demand is then used to estimate the goods flow per goods type. The model's primary application use case is in urban freight distribution, with its ability to estimate goods flow, freight traffic and investigate freight transport externalities.

Boerkamps et al. (2000) first applied the *good-trip* model to a case study of the city of Groningen in The Netherlands. Due to its application of the traditional four-step modelling paradigm to supply chains, it finds a right balance between four-step modelling and disaggregate modelling. Boerkamps et al. (2000) used the model in a case study for making a comparison between the logistical performance and

external impacts of three types of distribution systems. The model was also used to evaluate alternative distribution channels, using vans or pipelines for urban freight distribution in food retail. Asides being calibrated for the food retail sector, the model was also trialled for book stores to evaluate its flexibility.

Boerkamps et al. (2000) indicated that the *good-trip* model could estimate the impact of changes in different distribution systems. The model is also able to compute quantitative values for freight transport externalities such as emissions and other environmental impact indicators.

ii. ***De Jong & Ben-Akiva:*** A micro-simulation logistics model that considers the impact of logistics choices on the logistics system was developed by de Jong & Ben-Akiva (2007). The model operates at an origin-destination level and simulates logistics elements, such as shipment sizes and transport chain choices, for all origin-destination relations at a national scale. The authors describe the model as a logistics module within a more extensive freight modelling system. The transport chain choices represented in the model include sender, receiver, logistic chain, commodity type, value, model/vehicle type/loading unit, transhipment location, and the number of legs. The authors highlighted that other sophisticated models do not consider logistics elements as endogenous to the modelling process. This model also considers empty vehicles by reversing the flow in the opposite of the origin to destination direction. The authors, de Jong & Ben-Akiva, applied their model to freight systems in Norway and Sweden.

iii. ***FAME Model:*** Kawamura (2011) developed the FAME model. FAME translates to Freight Activity Microsimulation Estimator. FAME is a micro-simulation framework that uses agent-based modelling to represent actors within the logistics system and determines the goods flow through the freight transport chain. The authors cited a lack of disaggregated data on agents within the logistics system. Hence, detailed consideration is given to agents that are critical to decision-making within the logistics system. Individual decision-making agents with their specific characteristics and geographical distribution are introduced to the generation of company types. Trade relations between company types are determined in a supplier selection module. Within the transport chain, intermodal terminals, distribution, and consolidation centres are integrated. Consideration for logistics choices is via logistics chains. The number of stops and the means of transport selection is determined for each of the corresponding consignments and chains. Furthermore,

optimal shipment sizes for each transport chain are defined via logistics nodes. In this context, the authors created different combinations and transport chains to link suppliers and buyers. Within each transport chain, intermodal terminals, distribution, and consolidation centres are integrated.

iv. **EUNET 2.0:** EUNET 2.0 is a British regional British model for the "Transpeninne Corridor" by Ying Jin et al. (2005). EUNET 2.0 is a follow up to a sophisticated model, initially developed in 2000, that generated transport demand from spatial input-output modelling. However, the original version of the model did not consider logistics operations. The EUNET 2.0 was borne out of the availability of updated data sources and the need to identify logistics processes within transport models transparently.

It also contains a logistics module like other logistics models. This model deals with logistics processes by integrating logistical movements into a spatial input-output model. The usage of the EUNET 2.0 model focuses on development processes, providing a connection between regional economics and logistics. It provides a connection between regional economics and logistics, by forecasting freight transport demand as a function of economic transactions. Ying Jin et al. (2005) examined results generated from the EUNET 2.0 model, for the year 2001 (calibration year) and the year 2016 (scenario year). The results revealed changes in transportation costs and a shift in the utilization of regional distribution hubs for significant freight categories.

v. **LAMTA Model:** Fischer et al. (2005) developed the LAMTA model (Los Angeles Freight Forecasting model). This model is a multimodal freight transport demand model for the Los Angeles Metropolitan Area (LAMA). It includes support for logistics decision-making in freight transport. In modelling freight flows, the model considers logistics hubs (warehouses and distribution centres) as individual transport demand generators. The module responsible for this is known as the Transport Logistics Node module (TLN).

However, the TLN module models inter-zonal goods flows and not goods flow within the LAMA study area. Therefore, demand generation for long-distance haulage is computed as if they are from the logistics hubs within the study area. The TLN first describes the attributes of logistics hubs. Separate origin-destination matrices are then computed for each mode-commodity pair by providing O-D matrices as input to the TLN. The LAMTA model has been successfully applied, by Fischer et al.

(2005), for estimating freight flows between Southern California and the rest of the United States.

vi. **INTERLOG:** This is an agent-based approach to freight transport modelling developed by Liedtke (2009). This model examines transport behaviour in freight transportation while considering the decision-making entities within the logistics system. Liedtke (2009) developed three separate modules: generation module, sourcing module and simulation module. The *generation module* produces locations of various companies based on statistics. The *sourcing module* creates an Origin-Destination relationship for the shippers and recipients. This allows the generated companies to determine freight demand. The *simulation module* creates an interactive market where freight flows are converted to shipments and transport tours are generated. The INTERLOG model applies a bottom-up approach where interaction between shippers and carriers are simulated by auctioning contracts of carriage. Tour generation is the output of this simulation. The INTERLOG model has been calibrated using German data, according to Liedtke (2009), and several simulations were performed to determine the computational potential and limitations of the model.

vii. **Wisetjindawat et al.:** A multi-agent freight system focused on modelling freight distribution based on the movement of goods through supply chains has been developed by Wisetjindawat et al. (2012). The authors suggest a discrete choice approach to estimating freight distribution matrices between shipper and customer pairs. The authors term the structure of the model as a demand derived model. This implies that the recipients make the decision on which shipper is responsible for their goods. Two cost parameters are associated with purchases made by customers from suppliers: production costs and transportation costs. The model computes production costs using the land price while the transportation costs are computed using the transport cost between shipper and customer pairs. Wisetjindawat et al. (2012) applied this model to urban freight transportation in the Tokyo Metropolitan area. The commodity movement data of the Tokyo Metropolitan Goods Movement Survey (TMGMS) was used to calibrate the model. The authors cited data availability as a limitation of multi-agent transport modelling. This limitation is even amplified by the requirement of granular data on freight demand and supply at the microscopic level.

viii. ***Schroeder et al.:*** MATSim is a micro-simulation tool, developed by Balmer et al. (2008), that considers decision making actors as individual agents. Disaggregate data is a requirement for this modelling approach. Balmer et al. (2008) opined that enhanced accessibility to computing power is one of the driving factors of increasing adoption of microscopic models for large scale transport planning. In the MATSim framework, each decision-maker is represented individually as an agent. Each agent is thereafter equipped with attributes containing specific predefined parameters. The agents are loaded on a network, then several iterations of the simulation run are performed.

Schroeder et al. (2012) developed a multi-agent freight transport model where decision-makers can recognise changes in the simulation environment and make decisions based on those changes. The model developed by Schroeder et al. (2012) captured the intricacies of logistics operations where decisions are influenced by changes in policy and traffic situation. Schroeder et al. (2012) simulated passenger movements alongside freight traffic. This modelling approach establishes that freight transportation can be simulated with consideration of different policy and transportation measures.

ix. ***TAPAS Model:*** The TAPAS model, developed by Ramstedt (2008), demonstrates the application of multi-agent-based simulation for transport policy analysis. Ramstedt (2008) identified a set of decision-making actors within the freight transportation chain, then develops a multi-agent simulator where these decision-making actors are modelled as individual agents within a system. In the TAPAS model, the author captured the interaction between agents and their influence in decision-making within the system. The research pointed out that these decisions have a significant impact on logistics operations, the economy and the environment. Ramstedt (2008) also argued that agent-based models are potentially able to predict the actual environment of the logistics landscape. The TAPAS model has been applied to two scenarios on the East-West Transport corridor. The first scenario investigated the effects of a kilometre tax, on the transport corridor. The second scenario examined four measures that could potentially stimulate competition on the corridor.

x. ***SD Feedback Model:*** In a novel freight transport modelling approach, Thaller (2018) presented a dynamic model that couples a Macroscopic transport model with a microscopic transport simulation. This model considers the dynamic nature of the

transportation system. The model takes advantage of the aggregation of macroscopic modelling and the spatial resolution of microscopic modelling. The model framework is based on a feedback approach using three components: Macroscopic extrapolation (MEP), Microscopic transport simulation (MTS) and the feedback mechanism. The feedback mechanism is the coupling interface that disaggregates data from the MEP for use in the MTS and aggregates data the other way around. This model has been applied to investigate the impact of specific transport policy and logistics measures on transport, logistics and the environment.

xi. ***FREMIS (Freight Market Interactions Simulation):*** Implementing an agent-based modelling framework, Cavalcante, (2013) presented a freight model that forecasts freight flows by simulating interactions between individual agents in the freight market. The model framework uses competitive profit-making behaviour to represent carriers' behaviour towards seeking transport contracts. Two demand models, a shipment bundling model and carrier selection models were used to represent shippers' behaviour in the market.

Using learning models, agents could learn from previous interactions with other agents within the market. This FREMIS model has been applied to freight flows within the Greater Toronto and Hamilton Area freight market.

xii. ***Hunt & Stefan:*** This model has been developed by Hunt & Stefan (2007) as a tour-based model for simulating freight flows for Calgary in Canada. The model combines a tour-based approach and an aggregate approach. Three urban freight movements are considered within the modelling structure.

In the model, tour-based movements represented about 70% of the urban freight movements studied. The tour-based microsimulation employed Monte Carlo Techniques to assign attributes to individual tour. Then the tours are simulated based on specified attributes. Several iterations are performed until the last tour is completed. The model has been applied to freight movement of 37,000 truck tours in Calgary.

xiii. ***Joubert et al.:*** In the model presented by Joubert et al. (2009), freight activity chains are developed using an agent-based modelling approach. The framework of this model covers the simulation of generated freight activity chains, simultaneously with private vehicle activities. This simulation has been performed on a broad scenario in Gauteng, South Africa. A comparison of the simulation with observed data

revealed a level of spatial and temporal accuracy as well as a significant contribution of freight traffic to congestion and emissions.

xiv. ***Machledt-Michael:*** The model developed by Machledt-Michael (2000) simulates individual trip chains for urban and regional freight transportation. The model aptly represents trip chains, peculiar to freight transportation. These trip chains are used to determine distribution matrices, differentiated by vehicle categories and time periods. The matrices are then loaded on links and nodes of a network. The model developed by Machledt-Michael (2000) could carry out forecasts based on changed input variables such as structural variables of the traffic cells. The model has also shown to be responsive to changes in other model parameters such as changes in traffic flow and extended periods.

The models discussed in 2.4.3 give an insight into how modelling efforts have developed over time, in the scientific sphere of freight transport modelling. The development period for the selected models falls between 2000 to the 2018-year range. The selection of the models considered is based on the availability of full literature text during the period of review.

However, the selected models capture a wide range of modelling paradigms and cut across different stages in the evolution of freight models. A summary of these models is presented in Table 2.6, in reference to their typology and methodology. Table 2.6 displays, for each model, the level of aggregation, scale of analysis, modelling objective, modelling methods, time-horizon, and spatial resolution.

A noteworthy observation from this review is that disaggregate modelling has gained momentum in recent years, with more recent scientific research projects applying this level of aggregation. The growing adoption of "modelling at the microscopic scale" is also perceived from this review. A significant amount of these freight modelling studies have opined that agent-based microsimulations can represent the interactions of decision-making agents and their influence on logistics decisions. This is a significant reason behind the adoption of agent-based microscopic simulation (Cavalcante 2013; Joubert et al. 2009; Liedtke 2009; Ramstedt 2008; Schroeder et al. 2012; Thaller 2018; Wisetjindawat et al. 2012).

Moreover, scientific evidence presented in this review also points to the fact that agent-based microsimulation has been successfully used to study the impact of transport policy and logistics measures, on freight transportation (Huber et al. 2015; Ramstedt 2008; Schroder & Liedtke 2014; Thaller 2018; Zhang et al. 2018). These evaluations form a

scientific basis for the application of agent-based microsimulation to this research. This established modelling methodology will be applied to answer the research questions raised in the first chapter of this research project.

Table 2.6 Analysis of models based on typology and methodology (Source: Own Analysis)

		GoodTrip Model	de Jong & Ben-Akiva	FAME Model	EUNET 2.0ss	LAMTA Model	INTERLOG	Wisetjindawat et al.	Schroeder et al.	TAPAS Model	SD Feedback Model	FREMIS	Hunt & Stefan	Joubert et al	Machledt-Michael
Level of Aggregation	Aggregate	✓			✓	✓						✓	✓		✓
	Disaggregate		✓	✓			✓	✓	✓	✓	✓	✓		✓	
Scale of Analysis	Macroscopic	✓			✓	✓									✓
	Microscopic		✓	✓			✓	✓	✓	✓			✓	✓	
	Mesoscopic										✓	✓			
Modelling Objective	Flow-based	✓	✓	✓	✓	✓									
	Tour-Based											✓	✓	✓	✓
	Hybrid						✓	✓	✓	✓	✓				
Modelling Methods	Statistical Analysis	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Statistical Simulation												✓		
	Distribution Methods	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Optimization						✓		✓		✓				
	Equilibria														
	Temporal Simulation			✓			✓	✓	✓	✓	✓	✓	✓	✓	
Time-Horizon	Short-term												✓	✓	✓
	Medium-Term	✓	✓	✓		✓	✓	✓	✓	✓		✓			
	Long-Term				✓						✓				
Spatial Resolution	National		✓				✓								
	Regional			✓	✓	✓				✓			✓	✓	
	Urban	✓						✓	✓		✓	✓		✓	✓

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3. Research Methodology

This research project is an ex-ante assessment of the impacts of sustainable measures in the urban logistics system. An agent-based microscopic modelling approach will be used to model the measures for the case scenario. This chapter discusses the data used for the research, the preparation of this data for simulation as well as the modelling instruments applied for the simulation of the model.

3.1. Data Collection

The data used for this research project is collected from varying sources. However, secondary data collection is the primary data collection method used in this study. The data collected and their sources are outlined in this chapter.

Furthermore, the research study area is defined as the city of Berlin, in the Federal Republic of Germany. The study area, Berlin, will be referenced in this section and subsequent sections of this research project.

3.1.1. Population Data

The population dataset used for this research is derived from secondary population data collected and consolidated by Thaller (2018). The population dataset consists of entity types and their geolocation coordinates in the Gauss-Kreuger coordinate system (GK4). The entity types in the population dataset refer to private persons, commercial clients, and courier, express and parcel (CEP) service providers.

Further details about the consolidation for each entity type in the population dataset is summarized in the next sections.

3.1.1.1. Private Persons

The private persons' data is derived from an analysis of the number of people by age group in Berlin (Amt für Statistik Berlin, 2016). The age group is distributed into nine segments – (*0–9, 10–19, 20–29, 30–39, 40–49, 50–59, 60–69, 70–79, ≥80*).

The private persons' data, from Thaller (2018), consists of the type of actor, geocoordinates of their location, weight coefficient and the age group. The weight coefficient represents the number of private persons per location in the dataset. To get the actual individual private persons, the entity data is replicated by the weight coefficient such that a weight coefficient of 2 indicates that a single entity data must be doubled.

Implicitly represented within the population data, is the share of private customers of CEP service providers shown in Table 3.1. These shares are derived from Thaller's analysis of a DHL study conducted in 2010 (Thaller 2018).

Table 3.1 Share of private customers of CEP service providers (Source: Thaller 2018)

	Age Groups	Share of CEP customers
1	0–19	6%
2	20 – 29	36%
3	30 – 39	27%
4	40 – 49	15%
5	50 – 59	9%
6	≥ 80	6%

To align the age distribution of the share of CEP customers to the distribution of the synthetic population, Thaller (2018) makes certain suppositions. The *0 – 9* age group is assumed to have a zero per cent share of CEP service use and the *10 – 19* age group is assigned the 6% share. Likewise, the six per cent share for age group ≥ *60* is divided into three and the age groups *60 – 69, 70 – 79* and *80 – 89* are assigned two per cent share each. Table 3.2 displays the age distribution, respective shares and the potential customers of CEP service providers.

Table 3.2 Characteristics of the synthetic population. (Source: Thaller 2018)

	Age Groups	population	Share of CEP customers	CEP customers
1	0 – 9	287.290	0%	0
2	10 – 19	273.114	6%	16.387
3	20 – 29	506.652	37%	187.461
4	30 – 39	494.311	27%	133.464
5	40 – 49	591.014	15%	88.652
6	50 – 59	453.684	9%	40.832
7	60 – 69	398.706	2%	7.974
8	70 – 79	294.306	2%	5.886
9	≥ 80	143.598	2%	2.872

The age distribution and the share of CEP customers presented in Table 3.2, serve as an externally defined input during the initialization of the simulation world. Furthermore, georeferenced data points for the private person entities are included in the consolidated population data, provided as an input file, for initializing the simulation environment.

3.1.1.2. Commercial Clients

Datapoints for commercial clients are derived, from an evaluation of commercial activities generated from the OpenStreetMap database of Berlin, by Thaller (2018). Specifications regarding the numbers and types of commercial clients considered in Thaller's (2018) evaluation are presented in Table 3.3.

Table 3.3 Commercial location types. (Source: Thaller 2018)

Commercial Location Types	Number	Examples of Commercial Locations
Workplaces	2821	Political offices, Administrative buildings, Public buildings, Commercial offices, Travel Agencies, Police, Banks
Workplaces at educational institutions	386	Universities, Research Institutes
Shopping possibilities	5617	General retail trade, Shopping malls, Department stores, Clothing stores, Confectionery shops, Art shops, Medical supply stores, Other shops
Access points, shopping facilities	339	Petrol stations
Leisure facilities	8656	Gastronomy
Workplaces at Leisure facilities	1195	Tailor, Beauty salons, Hairdresser, Solariums.

3.1.1.3. CEP Service Providers

Datapoints of courier, express and parcel (CEP) service providers, are derived from Thaller's (2018) evaluation of the largest CEP service providers in Berlin. The data points used in this survey are the logistics nodes, particularly the distribution centres of these service providers. The CEP service providers in the dataset include distribution centre geocoordinates of DHL, UPS, Hermes, DPD and GLS. The geolocation coordinates provided in the population dataset are the actual locations the CEP service providers which have been converted into geocoordinates according to the Gauss-Kreuger coordinate system (GK4).

A total of 31 CEP distribution centres are included in the population dataset collected for this research project.

3.1.2. Network Infrastructure

For this research, the network infrastructure for Berlin, developed by Rieser, (2017), is used. The network consists of 27,663 links and 11,565 nodes. Each link on the network contains information about the link id, nodes at the start and end of the link, length, free speed, flow capacity, number of lanes, and modes allowed. On the other hand, each node on the network contains the node id and geocoordinates in the Gauss-Kreuger coordinate system (GK4). The free speed on each link is set at 6.71 m/s, to incorporate resistance on the network produced by passenger traffic. Ideally, this free speed value is converted into metres per second from kilometres per hour, using Olson & Nolan (2008) report on the average speed in Berlin. These values are consistent with the data being used, with respect to the period in which they have been gathered by Thaller (2018).

3.1.3. Vehicle Fleet of CEP Service Providers

To model the activities of CEP service providers, details regarding their fleet are required. The fleet details for this study were collected as required. In this study, it is assumed that the vehicle fleet for urban freight delivery comprises of light vehicles with a total permissible weight of less than 3.5-tonne. This assumption is derived from the regulation of commercial vehicles in Berlin. This regulation states that the use of vehicles, with a total permissible weight of over 3.5-tonne for commercial purposes, are subject to authorization.

Vehicle specifications for the CEP Service providers are derived by collating vehicle characteristics for a vehicle type and then computing the required values for initializing the simulation environment. The vehicle characteristics include:

- Purchase price of the vehicle
- Tank size and fuel cost of a full tank
- Engine performance and maximum range
- Transport costs: fixed costs, variable costs, and personnel costs
- Workshop/maintenance costs, depreciation costs, and interest costs (return on capital).

All the values for the vehicle characteristics except the transport cost values are derived from the fleet characteristics dataset of Thaller (2018). The calculations utilized for deriving the transport costs are presented in 3.1.4.

3.1.4. Transport costs

This section details how the values for the transport costs are derived:

i.   *Average Residual Value* [€/year]:

$$ARV = \beta_{RV} \times PP$$

where

β_{RV} = Residual value factor

PP = Purchase price [€]

ii.   *Interest Costs* [€/year]:

$$I = \frac{PP + ARV}{2} \times Ir$$

where

PP = Vehicle purchase price [€]

ARV = Average residual value [€/year]

Ir = Interest rate

iii.   *Depreciation Costs* [€/year]:

$$DC = \frac{PP - TP - ARV}{ASL} \times Dr$$

where

PP = Vehicle purchase price [€]

TP = Price of tyres [€]

ARV = Average residual Value [€/year]

ASL = Average service life per vehicle [year]

Dr = Depreciation rate

iv.   *Performance Depreciation Costs* [€/km]:

$$PDC = \frac{PP - ARV - TP}{VM} \times PDr$$

where

PP = Vehicle purchase price [€]

ARV = Average residual Value [€/year]

TP = Price of tyres [€]

VM = Total service mileage of vehicle [km]

PDr = Performance depreciation rate

v.   *Tyres Costs* [€/km]:

$$TYC = \frac{TP}{TM}$$

where

TP = Price of tyres [€]

TM = Mileage of tyres [km]

vi.   *Fixed Costs* [€/year]:

$$FC = I + DC + Ins + Oc$$

where

I = Interest costs [€/year]

DC = Depreciation costs [€/year]

Ins = Insurance costs [€/year]

Oc = Other costs [€/year]

(Other costs include costs for fleet management, parking of vehicles or garage costs which are constant for a period)

vii.   *Variable Costs* [€/km]:

$$VC = MC + FL + PDC + TC + LC$$

where

MC = Maintenance costs [€/km]

FL = Fuel costs [€/km]

PDC = Performance depreciation costs [€/km]

TC = Tyre costs [€/km]

LC = Lubrication costs [€/km]

viii.   *Personnel Costs* [€/year]:

$$PC = \frac{DS \times \beta_{PC}}{GWD \times DWH}$$

where

DS = Driver's salary [€/year]

β_{PC} = Personnel factor per vehicle

GWD = Gross working days [days/year]

DWH = Gross working days [hours]

ix. Fuel Consumption [litres/km] or [kWh/km]:

$$FLC = \frac{CP}{RG}$$

where

CP = Capacity [litres] or [kWh]

RG = Range [km]

The values required for deriving the transport costs, excluding the nine cost calculations explicitly defined in 3.1.4, are collated from Thaller (2018). These values are provided as constants during the preparation of input data for the model. Furthermore, the values derived in this section must be translated to fit the standards of the modelling instruments used. Details regarding the modelling instruments are explored in 3.2.

3.2. Modelling Instruments

As stated earlier in 1.2, agent-based simulation is used to model specific impacts of selected sustainable measures on courier, express and parcel delivery systems. To achieve this, two modelling instruments have been employed: MATSim and Jsprit. This chapter examines the modelling instruments applied in this research project.

3.2.1. Multi-Agent Transport Modelling in MATSim

MATSim, an acronym for Multi-Agent Transport Simulation Toolkit, is an activity-based, multi-agent simulation framework, implemented in Java. The modelling approach for MATSim is iterative. The system is initiated using an initial demand state, and then iterative runs are performed while agents simultaneously adapt their behaviour to the state presented on each run. (Balmer et al. 2008) MATSim is based on the coevolutionary principle where every agent, while competing for space-time on the transportation network, iteratively optimizes its daily activity schedule.

Each run in MATSim is usually a daily simulation of activities in 24-hour format. This implies that input data must be provided in accordance with the simulation standard. The transport costs calculation, illustrated in 3.1.4, must be translated to daily cost values.

For a typical MATSim model run, agents are equipped with a set of daily plans before initiation of the MATSim world. At the first iteration, agents simultaneously execute one of their plans and then proceed to optimise these plans with each subsequent iteration. An econometric utility function is deployed by each agent to score their plans at the end

of each iteration. The scoring function can be modified and adapted to suit research needs. Plans are rated good or bad by the agents after scoring. Agents also implement re-planning strategies that enable them to select new plans or modify existing ones. This process keeps on looping until the specified number of iterations have been completed, as shown in Figure 3.1. A state of equilibrium is reached when the agents can no longer optimise their plans further to get better plans. At this point, no better plan score can be generated. In the MATSim context, this is known as a *stochastic equilibrium* – a state where grouped agents cannot increase the satisfaction they derive from planning or altering their daily task or plans. (Horni et al. 2016)
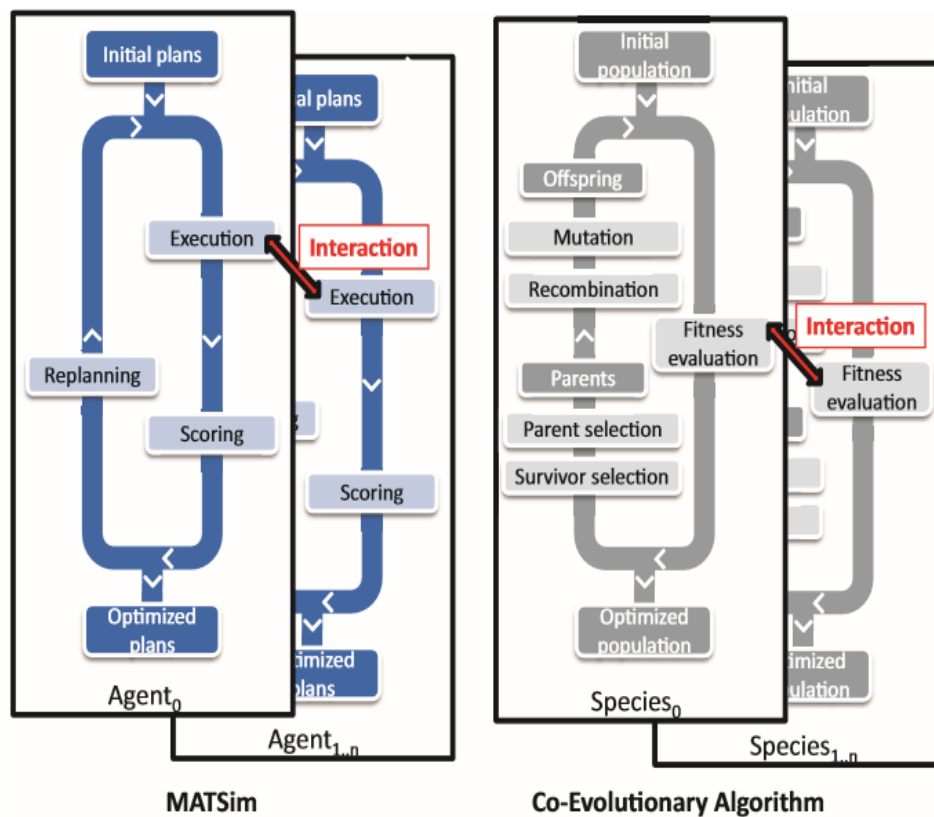

Figure 3.1 The co-evolutionary algorithm in MATSim (Source: Horni et al. 2016)

MATSim provides two internal Mobility Simulations, Queue Simulation (QSim) and Java Discrete Event Queue Simulation (JDEQSim). Mobility Simulation is done after the selection of the plan from memory by the agent during iteration. This MATSim cycle is shown in Figure 3.2. The mobility simulation, which determines the selection of plan scores, performs its runs and produces a plan performance.

After mobility simulation, around 10% of agents are permitted to clone the selected plan and modify this clone. The four dimensions are considered for MATSim at this stage, time (departure time, implicitly, activity duration), route, mode, and destination. Re-

planning entails agents optimizing their plans after each run. Each agent has a limited number of plans they can store in memory. If this limit is reached, the plan with the lowest score is eliminated from an agent memory. In the absence of re-planning, some agents select between existing plans.

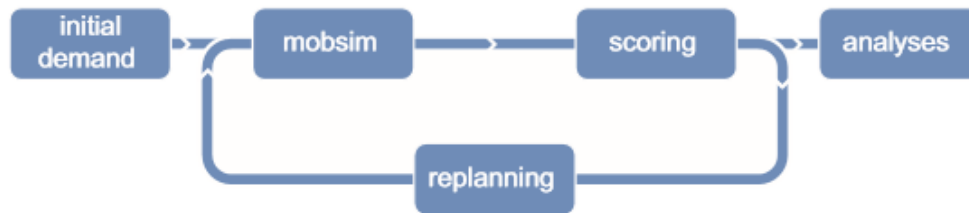*Figure 3.2 The MATSim cycle (Source: Horni et al. 2016)*

According to Horni et al. (2016), this state completes the iteration by evaluating the agents' experiences with the selected daily plans. To obtain the average population score stability, the iteration process is repeated. This produces a score development curve, as shown in Figure 3.3.
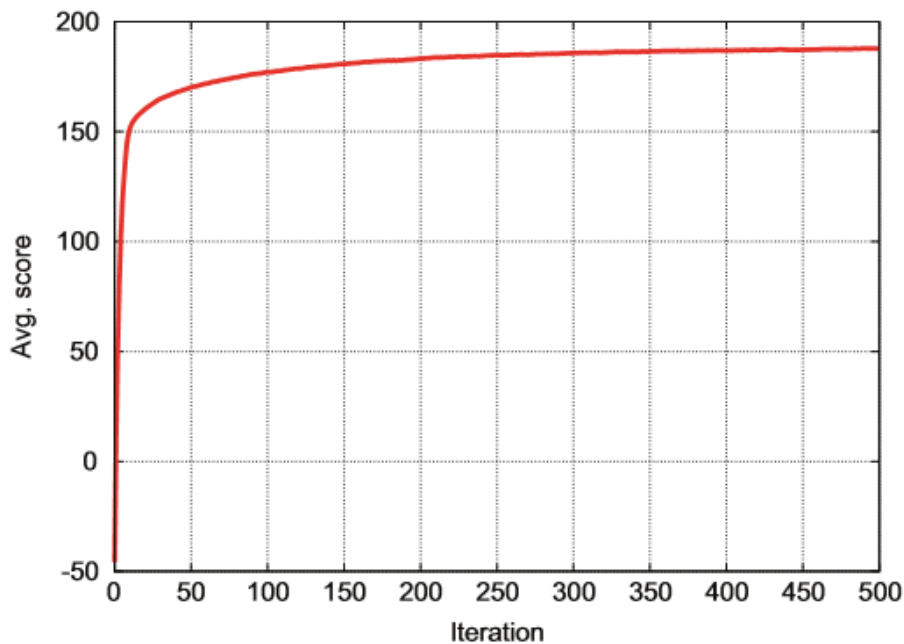

Figure 3.3 MATSim score development curve (Source: Horni et al. 2016)

MATSim provides a variety of tools and modules to model the interactions between travel demand and traffic flow (Balmer et al. 2008). Furthermore, with several contributions to the framework, there have been specialised modules included for specialised aspects of transport modelling. One of these modules is the MATSim freight module, highlighted in Figure 3.4, which provides customized implementations of agents in the freight transport system.
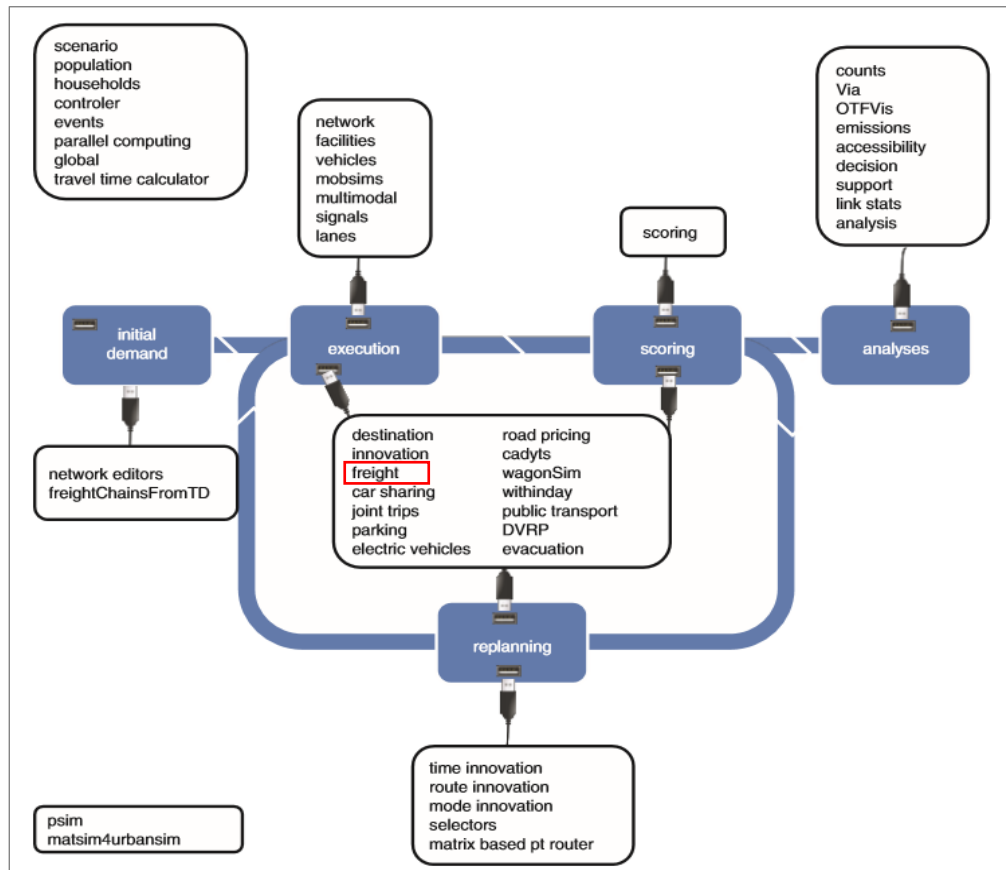
Figure 3.4 Modules connected to the MATSim cycle (Source: Horni et al. 2016)

Although MATSim was initially developed for passenger transport simulation, various studies have successfully implemented it for modelling freight transport (Schröder & Liedtke 2014, Schröder et al. 2012, Thaller 2018, Zhang et al. 2018). While these studies have a common attribute in the usage of the MATSim toolkit, the freight modelling processes slightly differ, as each study adapts the modelling process to suit the research objective under concern. For this research, the MATSim toolkit will be complemented with a vehicle routing algorithm, known as "Jsprit", to solve the logistics routing problem and create an initial plan for the MATSim run. The Jsprit freight module is discussed in the next section.

3.2.2. Jsprit Freight Module

Jsprit is an open-source toolkit based on the java programming language. It provides computational algorithms for solving vehicle routing problems and travelling salesman problems (Schröder 2014). A freight plugin in MATSim integrates Jsprit to model logistics decisions of freight carrier agents. Jsprit is regarded as a route optimisation tool, equipped with features for solving problems with constraints such as pickups and deliveries, heterogeneous fleets, finite and infinite fleets, multiple depots and time windows.

Jsprit has been used in combination with MATSim for research studies, to apply vehicle routing algorithms for modelling behaviour of freight agents and evaluating freight transport policy measures. Schröder & Liedtke (2014) use the MATSim/Jsprit combination to model the effect of differentiated freight measures in urban food retail distribution. Zhang et al. (2018) apply MATSim/Jsprit to analyse the implementation of cargo bikes for last-mile deliveries and the usage of parcel pick-up points in urban logistics. Thaller (2018) also employ MATSim/Jsprit, with a system dynamics approach to evaluate various policy measures for courier, express and parcel deliveries in urban areas. Previous applications of the MATSim/Jsprit integration serve as guidance for implementation in this study. The modelling process for this study is presented in 3.3.

3.3. Initializing the simulation environment

The required input data for the model is defined in 3.1. The modelling instruments are examined in 3.2. The next step is to initialize the modelling environment. This sub-chapter provides an overview of the necessary steps to initialize the model and begin the simulation run.

Initial demand is required to start the simulation world. For this study, the initial demand is defined externally by specifying the freight demand for each entity type described in 3.1.1. The population dataset explained earlier is also provided, in CSV-file format, as an input to the simulation world. The logistics nodes of CEP service providers and are also defined within the population dataset. Fleet characteristics of the CEP service providers, defined in 3.1.3, are also provided, as input, in an external properties file.

Upon running the model, the first module – demand preparation, is initiated. The population dataset, which contains geolocation coordinates of the entity types, is unpacked using the weights of the age distribution described in 3.1.1.1. Each entity is

loaded onto a link in the network. The logistics nodes, representing the CEP distribution centres, are then loaded on the network. Once this is complete, the customers send their order, the quantity of demand for goods, to the CEP service provider. These orders are assigned to the distribution centre, which is nearest to the customer. The distribution centres, therefore, only supply those customers who are assigned to this location.

When delivery destinations are in proximity, order requests are combined. This is performed by the CEP service providers, for private customers, after all, order requests are received. For commercial customers, the CEP service provider is informed of delivery time windows that he must adhere to when planning the route or choosing a route.

The next step is the transfer of the prepared demand to the Jsprit module, where the routing algorithm is executed. The vehicle routing algorithm, Jsprit, allows for the definition of vehicle fleet size. For this research, it is assumed that the initial finite fleet size is available to each distribution centre. However, the CEP service provider will have access to more fleets, when necessary, according to Jsprit stipulation. The following attributes of the CEP service provider are declared externally and randomly assigned to the distribution centres.

- Number of vehicles with specific vehicle characteristics
- Operating time window
- Number of orders/shipments per day from private and commercial customers
- Number and locations of private and commercial customers
- Mode of delivery to private and commercial customers
- The delivery time window for commercial customers

To generate the initial activity plans of the agents, optimal routes for the supply relations from the CEP locations to the private and commercial CEP customers is determined in Jsprit. The output of this step is the initial plans of the freight transport agents, and it contains the following attributes

- Start and endpoints of the respective tours (in this case the distribution centres of the CEP service provider)
- Points of the stops (the locations of the customers)
- Number of packages ordered per stop
- Delivery time window for commercial customers

The tour plans, generated from the Jsprit algorithm, are translated into MATSim activity plans to be supplied as an input into MATSim. The MATSim simulation is then executed. In the course of this, the route plans of the CEP drivers and the activity plans of the passenger vehicle traffic can be simulated at the same time on the infrastructure network in order to determine the level of traffic congestion and to examine the mutual influence

of the respective road users. However, this paper does not simulate the activity plans of the passenger vehicle traffic. The impact of passenger traffic, on overall traffic volume, is considered by adjusting the average link speed values, on the network, for the simulation. This adjusted network reflects traffic resistance and congestion levels due to passenger traffic.

Demand preparation
Initialisation of the simulation world

Initial demand
- *Network file*
- *CEP Service Providers*
- *Distribution Centres*
- *Transhipment location*
- *Fleet size*
- *Vehicle type*
- *Private customers*

Jsprit
Create tour plans for execution in MATSim

Tour Plans
- *Start and end points of each tour*
- *Points of delivery*
- *Number of parcels ordered per stop*
- *Mode of delivery for private customers*
- *Delivery time window of commercial customers*
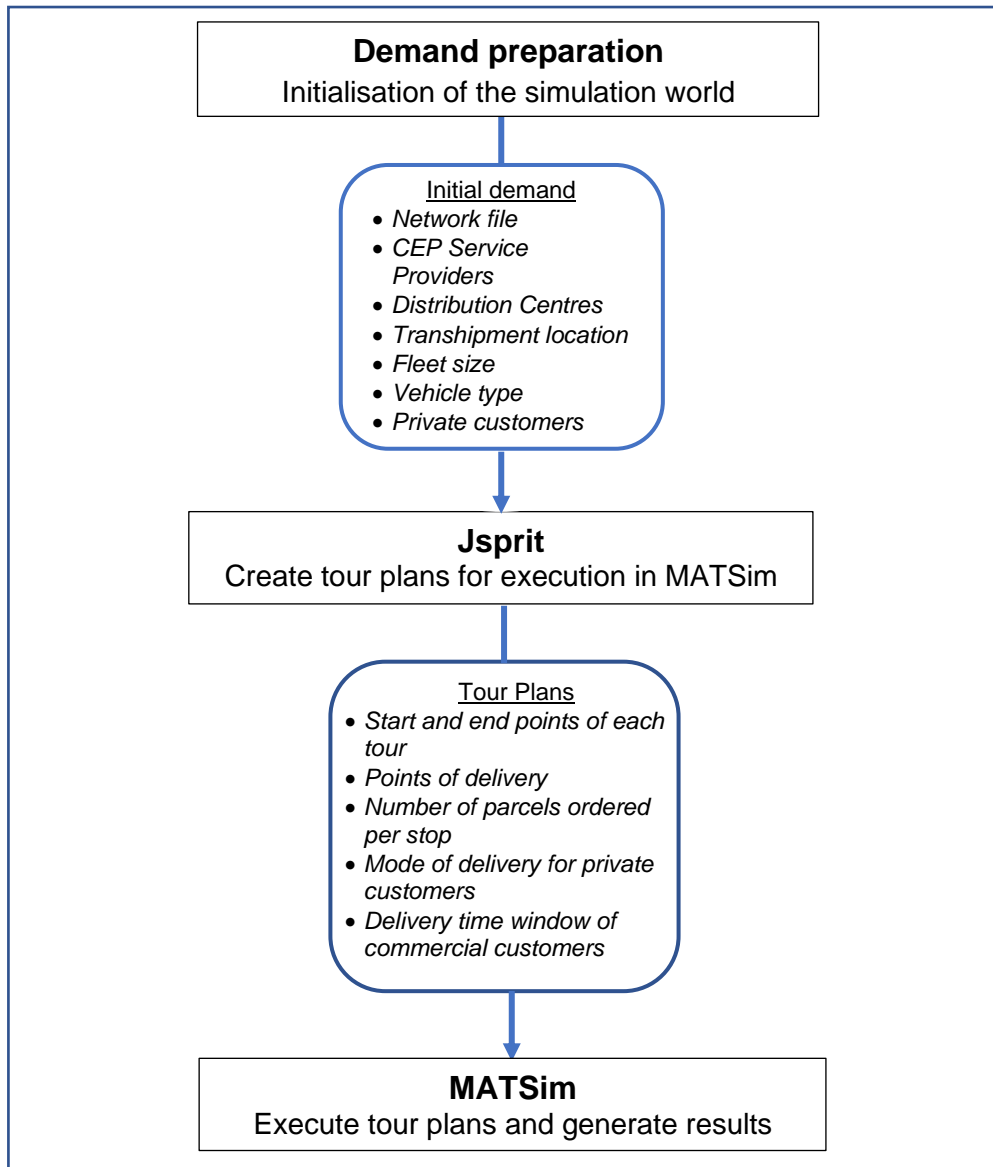
MATSim
Execute tour plans and generate results

Figure 3.5 Modelling Process for the research (Source: Own's representation according to Thaller 2018)

3.4. Data Analysis preparation

To analyse the results of the simulation run, the underlying computations for indicators and variables considered are detailed. This sub-chapter summarizes the calculations involved in the preparation of the data analysis module. The variables considered here are derived from the works of Browne et al. (2012) and Thaller (2018).

i. *Total demand for goods per day:* This is determined by summing up the number of delivered shipments after the simulation is completed.

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

where

tDG = total demand for goods or delivered shipments [parcels/day]

sh = shipment [parcel]

ii. *Total freight transport demand:* This is the number of vehicles used for the delivery of shipments per day. Since it is assumed that a vehicle can only perform only one tour per day, this value translates to the number of tours performed.

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

where

$tFTD$ = total freight transport demand [vehicles/day]

T = tour [vehicles]

iii. *Total transport distance:* The total transport distance is the total distance travelled or total mileage covered by the vehicle fleet used. Here, the road network infrastructure is used to determine the links that are driven by the vehicles. The lengths of the links are then summed up to determine the total transport distance.

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

where

tTd = total transport distance [metres/day]

L = length of link [metres]

iv. *Total Transport duration per day:* This is the time required by the entire fleet to deliver the shipment to the customers. This transport duration is accumulated within the simulation by each vehicle. It is computed by calculating the difference between the departure time from the distribution centre and the arrival time at the distribution centre.

$$tTT = \sum_{i=1}^{n} T_{arr} - T_{dep}$$

where

tTT = transport duration per day [seconds/day]

T_{arr} = arrival time at distribution centre [seconds]

T_{dep} = departure time at distribution centre [seconds]

v. *Total Fixed transport costs per day:* This is determined by the product of 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]

vi. *Total Variable transport costs per day:* This is determined by the product of total transport distance covered and the variable transport costs 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]

vii. *Total Personnel costs per day:* This is determined by the product of total transport time and the personnel costs per second.

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

where

PC_{day} = Personnel transport costs per day [€/day]

tTT = transport duration per day [seconds/day]

PC_{s} = Personnel transport costs per second [€/second]

viii. 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_{day} = Personnel transport *costs* per day [€/day]

ix. 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]

x. 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]

xi. 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 [litres/day]

β_{AB} = CO_2 conversion factor for AdBlue [kg/litre]

xii. Other Emissions per day (CO, HC+NO$_x$ and PM$_{10}$)

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

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]

Following the completion of the data analysis preparation, the next step is to outline the scenarios to be modelled. Development of the baseline scenario and other sustainable scenarios is discussed in the next chapter.

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4. Case Study

This chapter provides the basis for the model simulation phase. A definition of the evaluation borders of this research – scope of the research – as well as the study area is performed here. This chapter also entails the definition of the case scenarios to be modelled. These scenarios are outlined and explained herein. Furthermore, sources of the input data of the model as well as the formularization and parameterization of the model will be explained in the subchapters to follow.

4.1. Scope of the Research

The study area of this research is the city of Berlin. With a population of 3.8 million and a land area of 878 square kilometres, Berlin stands out as the largest city in Germany as well as in the whole of Europe.

This study will cover the area shown in Figure 4.1. The Berlin low-emission zone, which is peculiar to this research, is also depicted in Figure 4.1.
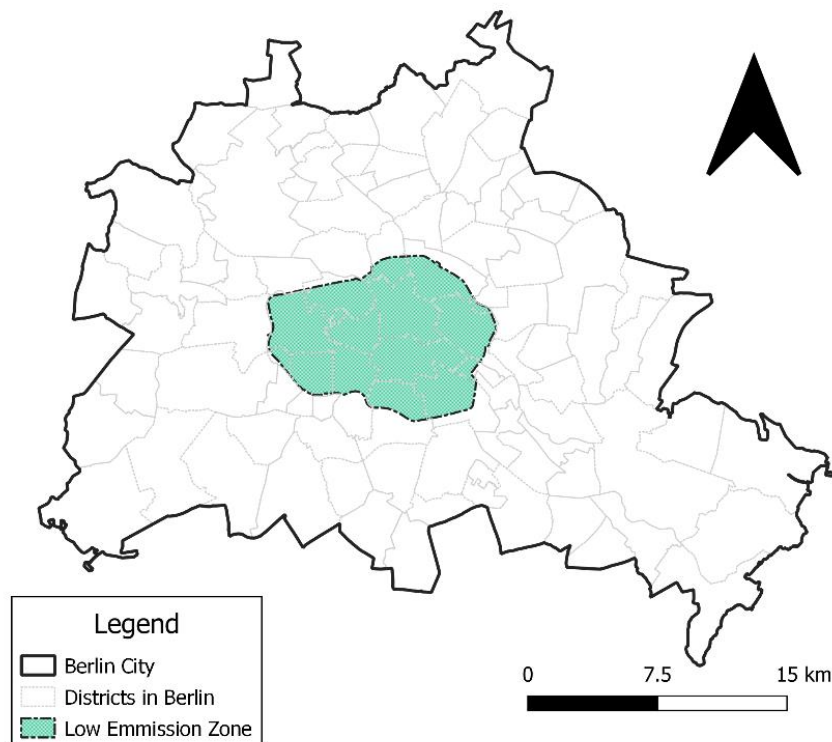
Figure 4.1 Map of Berlin, showing the low emission zone.
(Source: Own representation according to OpenStreetMap 2020)

4.2. Parameterization of the Model

To initialize the MATSim world, network infrastructure, location and population of the actors must be prepared. This sub-chapter discusses the specific details of the input data employed for this study. This sub-chapter puts values to the abstract definition of the modelling process described in 3.3.

This includes determining the framework conditions in the initialization of the synthetic world and generating the initial plans of the agents. The secondary data, stored in a georeferenced format, have been collated by Thaller (2018). This consists of the CEP service providers with their distribution centres, micro depots, private and commercial customers.

4.2.1. Private customers

The demand for goods to be delivered to private customers, on a typical day, is defined externally. For this research, this value is set to 2,973 parcels. It is assumed that only one request is made per private person. In this case, 2,973 parcels are delivered to 2,973 persons, randomly distributed using the age segments in 3.1.1.1. This is depicted in the model environment. The freight demand value has been scaled down to 3% of the 99,114 parcels defined by Thaller (2018). This is due to the high computational power required for simulating large datasets, which was unavailable for this research project.

In the demand preparation module, within the model, the private demand for goods is randomly distributed among potential customers of CEP service providers per age group. For delivery mode to private customers, only direct home delivery is considered. A delivery time window between 09:00 and 18:00 is considered for private customers, albeit, the operating time window for the CEP service provider is also considered for deliveries.

4.2.2. Commercial customers

Input data for commercial customers are also supplied in the georeferenced form. The commercial demand for goods to be delivered, on a typical day, to commercial customers is specified externally. For this research, the value is set to 5,130 parcels. This value has also been scaled down to 3% of the 172,296 parcels defined by Thaller (2018). In the synthetic world, the demand for goods per commercial customer is evenly distributed among all commercial customers, which are then allocated to a CEP service provider accordingly. The commercial customers are set to 570 commercial customers, spread

across the Berlin network. This value has also been scaled down to 3% of the 19,014 commercial customers defined by Thaller (2018). For delivery mode to commercial customers, only direct delivery is considered. However, only the specified time window, between 09:00 and 14:00, is considered for commercial customers. During route planning, the delivery time window of commercial customers is considered to get through traffic efficiently and meet delivery times.

For both private and commercial customers, the characteristic of choice between different CEP service providers is not considered. This means it is assumed that all locations within the study area are served by the same CEP service provider.

4.2.3. CEP service providers

Distribution centres of the CEP service provider for the study area are available in the georeferenced form. The number of distribution centres, initialised in the model environment, is set to 10. The fleet size of the CEP service provider is specified externally using data from Thaller (2018). For this research, two vehicle-types with a maximum allowable gross weight of 3.5 tonnes are considered. The operating time window of the CEP service provider and the start and end times for the vehicles are specified externally. In the context of this research, the characteristic of "choice between different CEP service providers" is not considered for both private and commercial customers. It is assumed that all distribution centres in Berlin belong to the same CEP service provider.

4.2.4. Fleet of CEP Service Providers

The fleet size and vehicle types of the CEP distribution centres are defined externally and supplied as input to the simulation world. The fleet size is set to an initial value of 3 vehicles. The fleet size is increased when more trucks are needed to perform deliveries. Vehicle capacity is not considered a restrictive factor as the driver agents can only deliver a limited number of packages during their working hours. Characteristics of the vehicle-type considered in this research are derived from the Mercedes-Benz Sprinter (ADAC 2019). The fleet size and vehicle types are uniform for all distribution centres considered. The characteristics of the vehicle type considered are summarized in Table 4.1.

Table 4.1 Vehicle characteristics of the Mercedes Sprinter 316 CDI.
(Source: ADAC 2019)

Parameters	Values
Vehicle Type	Light-duty truck
Fuel source	Diesel
Vehicle weight class	3.5 tonne
Payload (in kg)	1475 kg
Permissible total weight (in kg)	3500 kg
Empty weight	2025 kg
Volume (in m³)	7.5 m³
Battery size (in litres)	75.0 l
Range (in km)	872 km
Fuel consumption (litres/km)	0.086 l/km
Maximum speed (in km/h)	150 km/h

4.2.5. Emission conversion factors

To analyse the results from the simulation and determine emission values, conversion factors are applied, as defined in 3.4. Upon completion of the simulation, emission values are determined for the following emissions: CO_2, CO, PM_{10} HC and NO_x. The conversion factor for diesel drivetrain, applied for CO_2 emissions is set to 2.63kg/l. This is based on Thaller's (2018) specification, using the reported value of the Verkehrsrundschau (2014). Although electric vehicles do not produce emissions while driving, their emission footprints can be traced to the source of electricity for charging. The conversion factor for electric drivetrains, applied for CO_2 emissions is set to 0.47kg/kWh. This value is based on Icha & Kuhs' (2020) well-to-wheel conversion factors for the year 2018. The conversion factors for AdBlue CO_2 emissions, set to 0.24kg/l and the factors for pollutant emissions (CO, HC+NO_x and PM_{10}) are based on Thaller's (2018) specification. Table 4.2 Emission conversion factors summarizes the emission conversion factors used in the study.

Table 4.2 Emission conversion factors Source: Thaller (2018), Icha & Kuhs (2020)

| Emission Type	Conversion Factor
CO_2 Conversion Factor Electricity (Well-to-Wheel)	0.468 kg/kWh
CO_2 Conversion Factor Diesel	2.63 kg/l
CO_2 Conversion Factor AdBlue	0.238 kg/l
CO Conversion Factor Diesel	0.00024 g/m
PM_{10} Conversion Factor Diesel	0.00093 g/m
HC+NO_x Conversion Factor Diesel	0.00098 g/m

4.3. Definition of Case Scenarios

This chapter discusses the development of scenarios to be modelled. Three scenarios are modelled for this research project. The first scenario is a baseline scenario that captures the current situation of the system, with respect to the collection period of the data being used. The other two case scenarios involve a varied combination of a selection of measures previously discussed in 2.3. The two case scenarios build upon the baseline scenario. Selected sustainable measures are introduced to the baseline scenario through interactions between different entities in the logistics system. The selected measures to be modelled are discussed in the following section.

4.3.1. Selected Sustainable Models for the Case Study

For scenario modelling, three measures have been selected for implementation. One measure has been selected from each of the categories of measures discussed in 2.3. The selected measures are Zero-emission zones, Micro-depots, and Fleet electrification. The basis for selecting these measures and their characteristics will be discussed below.

i. *Zero-emission zones*: This measure is implemented in the scenario as a transport policy measure. Zero-emission zones are a more restricted version of low-emission zones, discussed in 2.3.1. In the logistics system, the policymakers in government are usually responsible for implementing transport policies. Also, these measures serve as a drive for specific changes within the system as the logistics providers must adapt to newly implemented policies.

For this scenario, the zero-emission zones are implemented using the infrastructure of the existing low-emission zones in berlin. The underlying measure here is to restrict access to all logistics vehicles that produce emissions. Using this measure, only carbon-neutral vehicles will be granted access to the zero-emission zones.
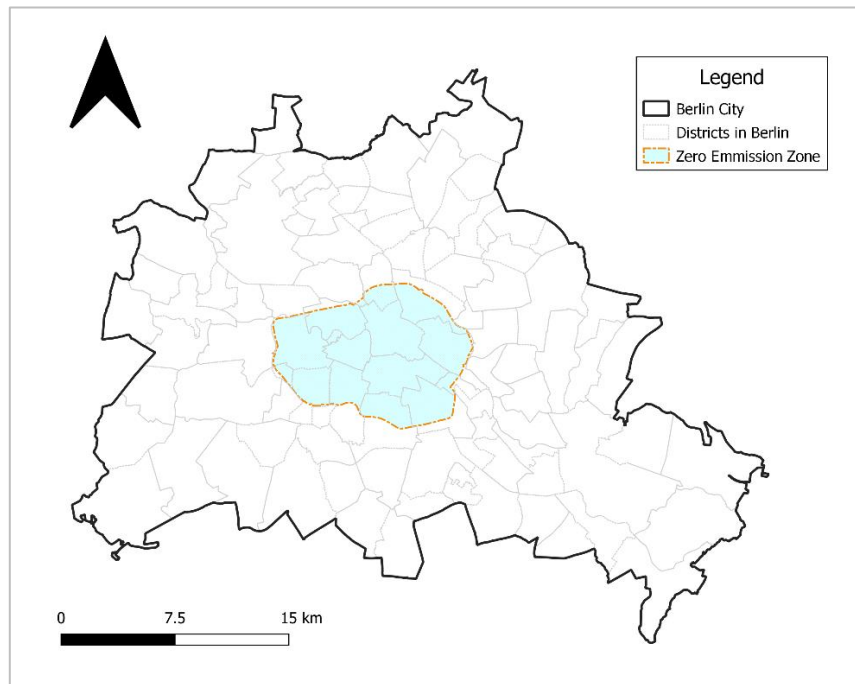
Figure 4.2 Map of Berlin showing the zero-emission zone of the integrated measures scenario.
Source: Own representation

A zero-emission zone measure has been selected, as it builds on an existing sustainable measure known as low-emission Zones. The concept of low-emission zones has been discussed earlier in this study in 2.3.1; however, the gains have not been significant as expected. An extended version, in the form of zero-emission zones, has been selected to investigate the impacts of policy restrictions on urban freight transportation.

ii. Micro-*Depots*: This measure is implemented in the scenario as a logistical measure. The concept of micro-depots has been examined in 2.3.2. For this scenario, micro-depots are implemented as a reactionary measure, by logistics service providers, to adapt to transport policy measures, put in place by policymakers. These micro-depots serve as a facility where parcels can be delivered before onward delivery to recipients.

Micro-depots have been selected as one of the measures to be implemented due to its practicality and proof of concept. Micro-depots are an already existing innovation which has proven to be practically useful in trans-loading delivery operations. The concept of this measure is to create a location outside the zero-emission zones, where parcels can be delivered. Transloading from the micro-depots will be performed by a carbon-neutral vehicle which will be discussed in the next measure.

iii. *Fleet Electrification*: This measure is implemented as a technological measure within the integrated scenario. Fleet electrification has been discussed in 2.3.3, under *vehicle engine design*. This measure was selected, considering the need to trans-load parcels from the micro-depots outside the zero-emission zone, to the recipients within the zero-emission zone.

The concept of electric vehicles for urban freight transportation has been widely discussed as a potential alternative for sustainable urban freight distribution. Some logistics service providers already have a significant number of electric vehicles within their fleet, and more are making progress in converting their current fleet to electric drivetrains (DHL 2020; Hermes 2020; UPS 2020). This increasing adoption of electric freight vehicles is the reason for selecting this measure as the technological measure to be implemented.

For this research, the vehicle characteristics of the Mercedes eVito will be used to simulate an electric delivery vehicle. While there are several types of electric vehicles, this vehicle has been selected because it is a light-duty truck, commonly used for last-mile delivery. The Mercedes eVito also satisfies the proof of concept, as it is already being used as an urban freight vehicle. Table 4.3 shows the characteristics of the electric freight vehicle used in the integrated scenario.

Table 4.3 Vehicle characteristics of the Mercedes eVito.
(Source: Mercedes Benz, 2019)

Parameters	Values
Vehicle Type	Light-duty truck
Fuel source	Electricity
Vehicle weight class	3.5 tonne
Payload (in kg)	1016 kg
Permissible total weight (in kg)	3200 kg
Empty weight	2184 kg
Volume (in m³)	6. m³
Battery size (in kWh)	41 kWh
Range (in km)	150 km
Energy consumption (kWh/km)	0.27 kWh/km
Maximum speed (in km/h)	120 km/h

4.3.2.   Scenario 1: Baseline scenario

In this scenario, a business as usual mode of operation is simulated. The logistics system is simulated using the prepared data without including any measures. The purpose of this scenario is to give an overview of the situation of the system when it is without any new measure. This will provide a basis for comparison after the measures are included in the integrated measures scenario. For this scenario, the attributes of the diesel vehicle type, used in the simulation, is summarised in Table 4.4.

Table 4.4 Vehicle attributes for the diesel vehicle type.
(Source: own computation according to ADAC, 2019)

Parameter	Value
Engine type	Diesel
Permissible total weight	3.5 t
Maximum loading capacity	160 [parcels/vehicle]
Fixed costs	51.439936795 [€/day]
Variable costs	0.000343626 [€/m]
Time-dependent costs and/or personnel costs	0.004200975 [€/s]
Fuel consumption	0.000112 [l/m]
AdBlue consumption	0.000001501 [l/m]
Maximum velocity	42 [m/s]

4.3.3.   Scenario 2: Partial Fleet Electrification in Study Area

In this scenario, fleet electrification is implemented by introducing an electric vehicle to the vehicle fleet of the CEP service provider. Here, vehicle characteristics of the Mercedes-Benz eVito, shown in Table 4.3, is used to represent an electric vehicle type. However, the vehicle characteristics have been translated to fit the requirements of the simulation input data. The vehicle attributes used for the simulation is presented in Table 4.5.

Table 4.5 Vehicle attributes for the electric vehicle type.
(Source: Own computation according to Mercedes Benz, 2019)

Parameter	Value
Engine type	Electric
Permissible total weight	3.5 t
Maximum loading capacity	120 [parcels/vehicle]
Fixed costs	51.071919465 [€/day]
Variable costs	0.00026399 [€/m]
Time-dependent costs and/or personnel costs	0.00420098 [€/s]
Electricity consumption	0.0003 [kWh/m]
Maximum velocity	33.33 [m/s]

4.3.4. Scenario 3: Zero-Emission Zone, Micro-Depots and Fleet Electrification

For the third scenario, the selected measures examined in 4.3.1 have been combined to depict an integrated scenario. Since the logistics environment to be modelled functions as a system, the different measures must be implemented by actors interacting within the system. The transport policy measure, in the form of a zero-emission zone, is implemented by policymakers in government. The logistical measure, in the form of micro-depots, is implemented by logistics service providers. The technological measure, in the form of fleet electrification, is also implemented by logistics service providers.
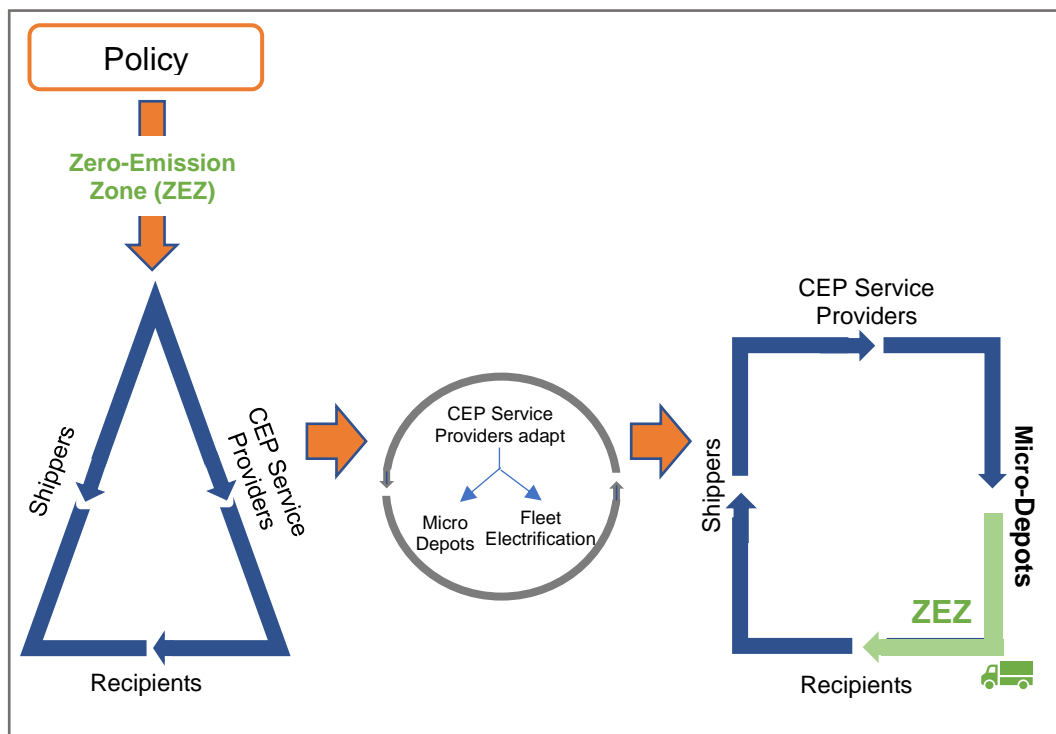

Figure 4.3 Integrated Measures Scenario. (Source: Own Representation)

As mentioned earlier, certain measures are reactionary, implemented to adapt to specific scenarios. In some cases, innovative developments within the logistics sector result in the implementation of new measures by logistics service providers. However, in this scenario, the policymakers kickstart the changes in the system by implementing policy, as shown in Figure 4.3. The other actors within the system must comply by developing and implementing new measures to adapt to this new policy.
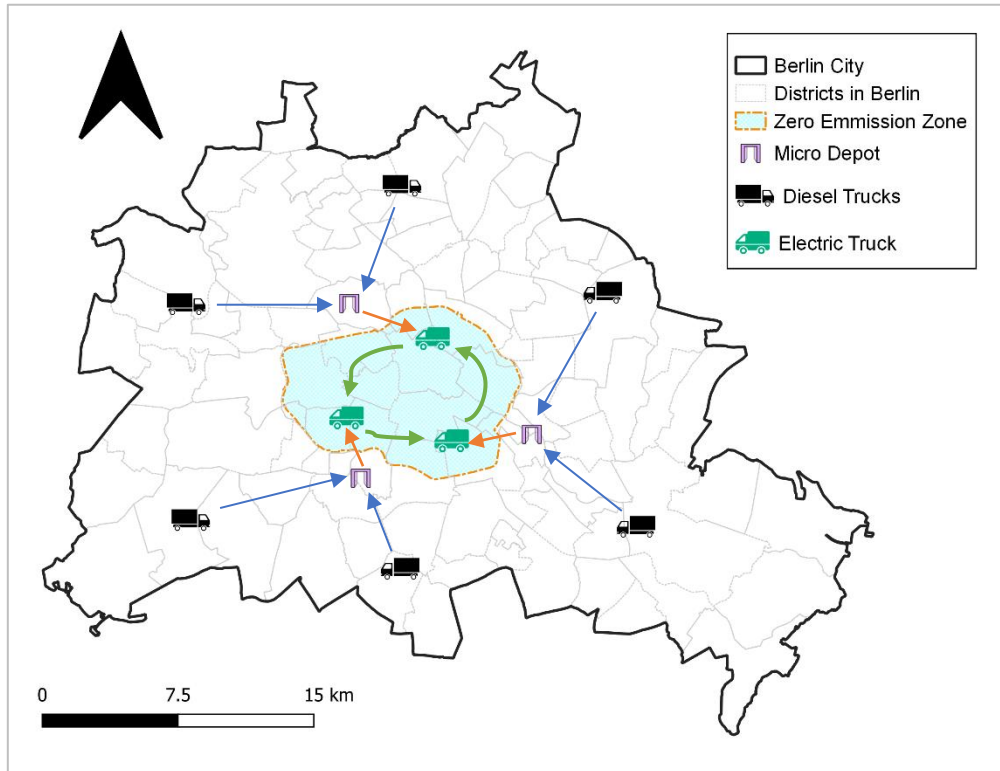
Figure 4.4 Map of Berlin showing the integrated measures scenario. Source: Own Representation

4.4. Preparing the model environment for the case scenarios

Following the declaration of the input parameters and definition of the case scenarios to be modelled. The overarching modelling procedure has already been detailed in sub-chapter 3.3. However, the specific process implemented for the case scenarios is yet to be discussed. This chapter provides specific details regarding the demand initialisation for the scenarios to be modelled.

After loading the population dataset, order requests must be sent by private and commercial customers. These requests are processed by the distribution centre, which is closest to the recipient. During the processing of these requests to create an initial demand, a function is used to combine deliveries to locations within proximity. This is done to avoid several trips by different vehicles to the same location. This optimization of deliveries is only performed for private customers due to the low number of parcels ordered per private customer.

To combine deliveries, a point is created for each link on the network. This point is known as the "combined delivery point". For every request made to by a private customer, the nearest link to the customer is computed and the customer's order request is added to the list of orders assigned to the combined delivery point of the nearest link to the customer. This is not the same as a parcel station or parcel shop implementation; instead, this is to simulate realistic delivery tours where deliveries can be made to several buildings on the street by one driver. This combined delivery is used to create the origin-destination pair of the service provider to the recipient, which is then used to schedule tours.

The combined delivery concept is used for all three scenarios; however, due to the introduction of a micro-depot, to simulate a two-step distribution, in scenario 3, a slightly adjusted implementation is used. Before processing deliveries, a check is made to determine if the customer's location is within the zero-emission zone (ZEZ) before processing the order request. If the customer's location is not within the ZEZ, the order is processed typically using the combined delivery function. Otherwise, the order is redirected to the micro-depot, which is closest to the customer. The micro-depot then performs its own processing of the request using the combined delivery request. The check to determine if a customer's location is in the ZEZ is done to both private and commercial customers. The rest of the modelling process is executed as described in sub-chapter 3.3.

Following an establishment of the case study and development of case scenarios, the results of the simulation, as well as discussions, are presented in the next chapter.

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5. Results

This chapter presents an evaluation of the results of the model. To analyse the results of the model, an analysis module has been developed, which is executed after the simulation run is completed. Results of the simulation results from the three case scenarios will be examined side by side. This will facilitate a comparative basis for evaluating the impact of the sustainable measures implemented. Since MATSim operated a 24-hour simulation period, the results generated from the model environment are interpreted as results for a day of logistics activities.

5.1. Evaluation of results

5.1.1. Vehicle distance travelled

Here, the results for the number of vehicles required, total distance travelled, the average distance travelled, and fuel consumption is evaluated.

5.1.1.1. Number of Vehicles Required

The number of vehicles required for the distribution of parcels varied considerably across the three scenarios, as shown in Figure 5.1. The vehicle requirement is observed to be higher in the two case scenarios with sustainable measures implemented, with scenario 3 having the highest number of vehicles required.
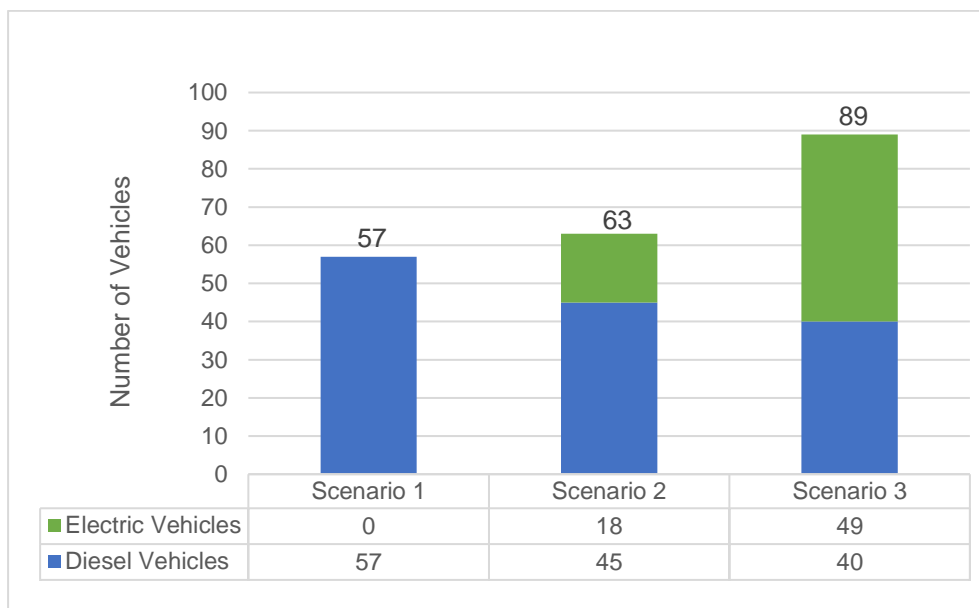

	Scenario 1	Scenario 2	Scenario 3
■ Electric Vehicles	0	18	49
■ Diesel Vehicles	57	45	40

Figure 5.1 Vehicle requirement for freight distribution

Compared to the baseline scenario 1, the second scenario required about 11% more vehicles while the third scenario required about 56% more vehicles. The 11% increase in vehicle usage could be associated with the fact that the electric vehicles used in the model are depicted to have a loading capacity, which is 25% lesser than the diesel vehicles. The 56% increase in vehicle usage could be attributed to the two-step distribution, which is simulated in scenario 3, requiring new vehicles from the micro-depot to the final delivery point. The increase in vehicles used could also be as a result of the delivery optimization used in the model, described in 4.4. This delivery combined delivery function might not adequately depict the logistics optimization used by CEP service providers.

Furthermore, in scenario 2, the ratio between diesel and electric vehicles is approximately 70:30. This correlates with the specification of 30% electric vehicles in the operating fleet, implemented as a sustainable measure in the second scenario.

5.1.1.2. Average Freight Distance Travelled

The average freight distance travelled, recorded in the simulation, are lower in scenario 2 and scenario 3. In the second scenario, a 26% reduction in average distance travelled is recorded for diesel vehicles compared to the baseline scenario 1.
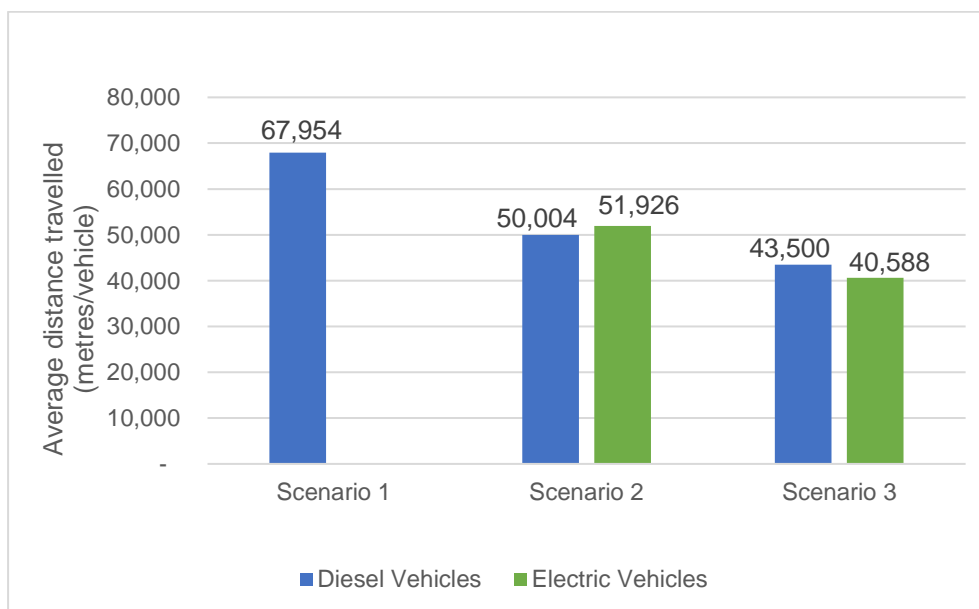

Figure 5.2 Average distance travelled

The combined (diesel + electric) average distance travelled for scenario 2 is 50,965m, which puts the overall reduction in average distance travelled at 25%, compared to

scenario 1. In scenario 3, an 18% reduction in average distance travelled is observed when compared to scenario 3 and 38% reduction when compared to scenario 1. However, the reduction in average distance is observed to correlate with the increased vehicle utilisation highlighted in 5.1.1.1. This implies that the more vehicles used in operation, the lesser the distance a vehicle has to travel.

5.1.1.3. Total Freight Distance Travelled

The total distance travelled recorded for scenario 2 and scenario 3 is lesser than the total distance recorded for scenario 1, as illustrated in Figure 5.3. It is also observed that the total distance recorded by scenario 2 is the lowest of all three scenarios, with a reduction of 18% compared to scenario 1 and 14% reduction when compared to scenario 3. Comparing the total distance travelled for electric and diesel vehicle types, a closer look at Figure 5.3 reveals that diesel vehicles in scenario 2 travel approximately 23% more distance than in scenario 3. Scenario 3 is also observed to have a larger ration of distance travelled by electric vehicles compared to scenario 2. This could be attributed to the sustainability measure that prescribes the use of electric freight vehicles within the zero-emission zone, in scenario 3.
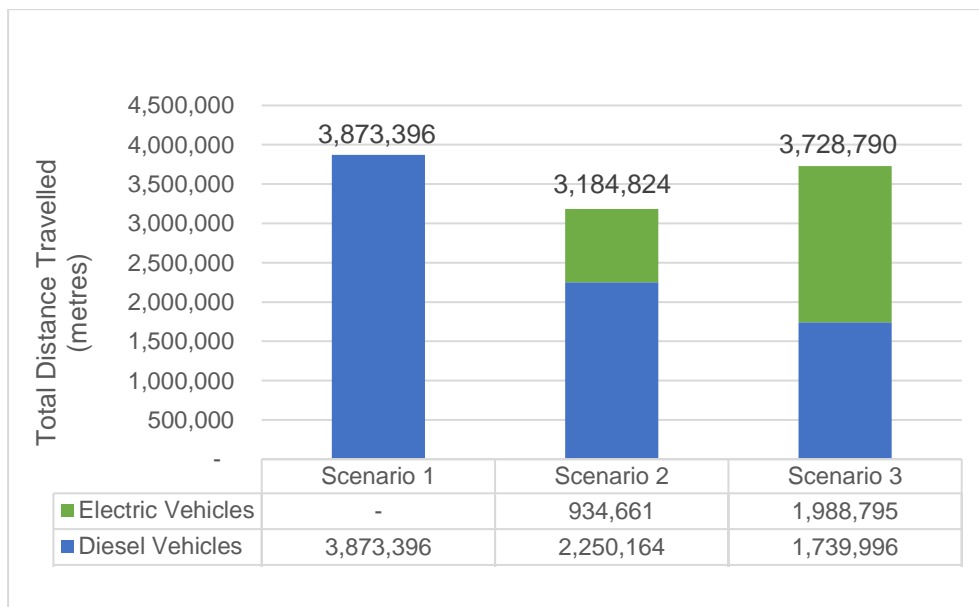

	Scenario 1	Scenario 2	Scenario 3
Electric Vehicles	-	934,661	1,988,795
Diesel Vehicles	3,873,396	2,250,164	1,739,996

Figure 5.3 Total distance travelled

5.1.2. Transport Costs Results

In this subchapter, the recorded results for the fuel consumption costs, fixed costs, variable costs, personnel costs, and total costs are evaluated.

5.1.2.1. Fuel Consumption Costs

In Figure 5.4, a distinction between consumption values for the two vehicle-types are made. For scenario 2 and scenario 3, the bar on the left is used to depict consumption values for diesel drivetrain in litres (l), the middle bare depicts the total cost of fuel consumed in Euros (€), while the bar on the right depicts consumption for the electric drivetrain in kilowatt-hours (kWh). The bars illustrated for scenario 1 only depicts consumption values for diesel drivetrain in litres (l) and the total cost of fuel consumed in Euros (€). Since no electric drivetrain is considered for scenario 1, no electricity consumption values are recorded. The consumption values illustrated in Figure 5.4 represents the total consumption for all vehicles operated for freight distribution in the model environment.
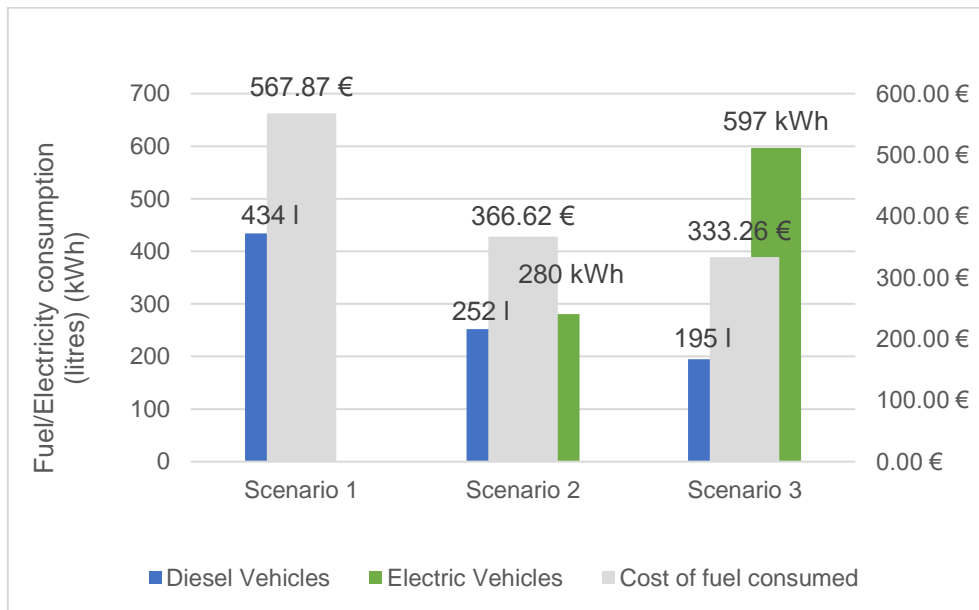

Figure 5.4 Total fuel consumption values

It is important to reiterate that the values recorded for fuel consumption are based on the vehicle types represented in the model environment. This has been established earlier in Table 4.4 and Table 4.5 of Chapter 4.

However, while diesel consumption in scenario 2 and scenario 3 are relatively lesser than scenario 1, the electricity consumption recorded is high due to the difference in the

maximum range attainable by electric vehicles. This perception of high electricity consumption is, however, negligible when the diesel cost per litre and the electricity cost per kWh are considered. This is depicted in Figure 5.4 as the cost of fuel consumed. From this, scenario 3 has the best fuel consumption costs, closely followed by scenario 2.

5.1.2.2. Fixed Costs

The fixed costs for each vehicle serve as an input for the calculation of total fixed costs for all operated vehicles. The fixed cost consists of insurance costs, interest costs, depreciation costs, shelter/ garage costs and fleet management costs. These costs are calculated in Euros per day (€/km), which indicates its constancy per day, depending on the number of vehicles in operation.

It is observed that the fixed costs recorded are directly proportional to the number of vehicles utilised in operation. This implies that the higher the vehicle utilisation, the higher the fixed costs, as shown in Figure 5.5.
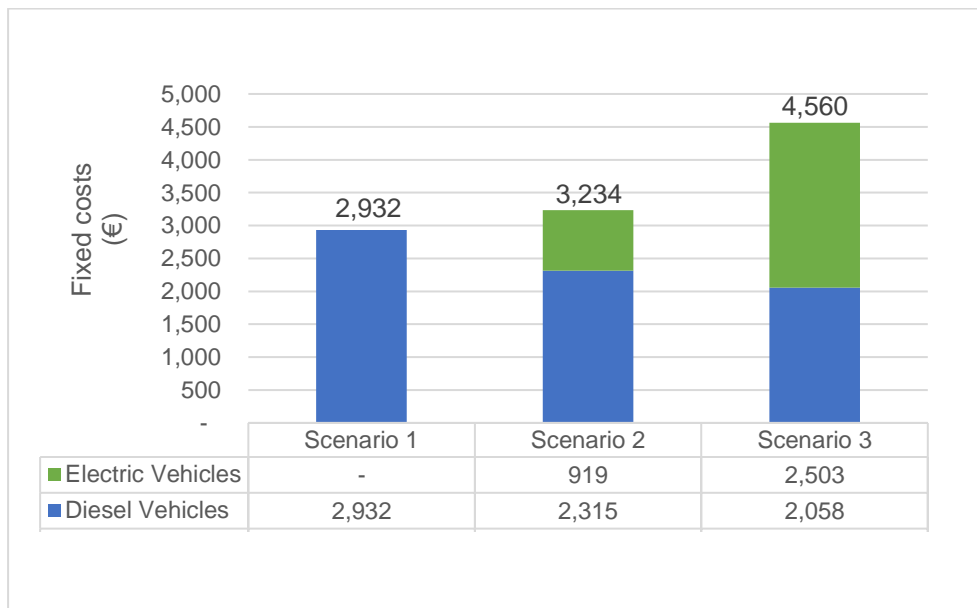

	Scenario 1	Scenario 2	Scenario 3
■ Electric Vehicles	-	919	2,503
■ Diesel Vehicles	2,932	2,315	2,058

Figure 5.5 Total Fixed Costs

5.1.2.3. Variable Costs

Like the fixed costs, the variable costs for each vehicle serve as an input to the calculation of total variable costs for all operated vehicles. The variable costs consist of vehicle maintenance costs, fuel costs, performance depreciation costs, and tyre costs. These costs are calculated in Euros per kilometre (€/km), which indicates its variability per kilometre travelled.

It is observed that the variable costs recorded are directly proportional to the total kilometres travelled, as shown in Figure 5.6.
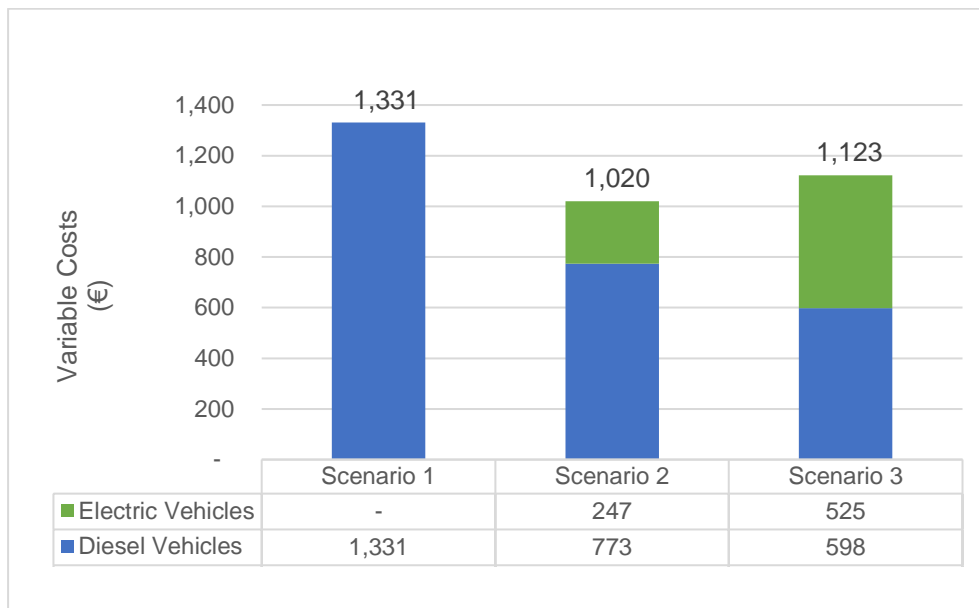

	Scenario 1	Scenario 2	Scenario 3
■ Electric Vehicles	-	247	525
■ Diesel Vehicles	1,331	773	598

Figure 5.6 Total Variable Costs

5.1.2.4. Personnel Costs

The personnel costs are a time-based cost, depicting the cost of the personnel operating the freight vehicles. It is observed that the personnel costs recorded in Figure 5.7. is expectedly directly proportional to the total kilometres travelled. This implies that the distance travelled in the model environment corresponds to the time-driven.
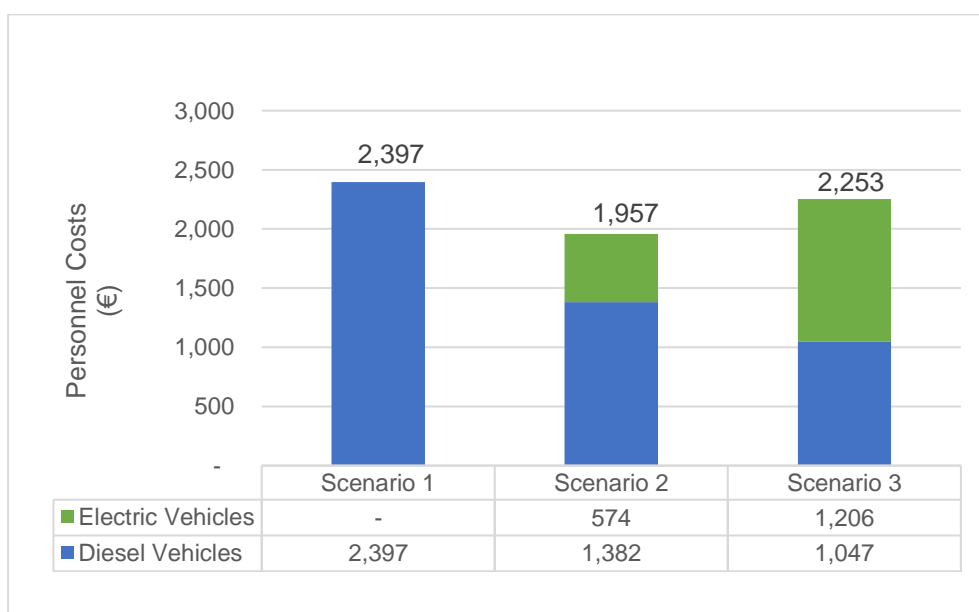

	Scenario 1	Scenario 2	Scenario 3
■ Electric Vehicles	-	574	1,206
■ Diesel Vehicles	2,397	1,382	1,047

Figure 5.7 Total Personnel Costs

5.1.2.5. Total Operating Costs

The total costs illustrated in Figure 5.8 is a sum of the fixed costs, variable costs, and personnel costs of each scenario under evaluation. The total cost for scenario 3 is the highest of the three scenarios which are due to the high fixed costs recorded in 5.1.2.2. Scenario 2 has the best total costs among the three scenarios, having a 5% reduction in costs compared to scenario 1.
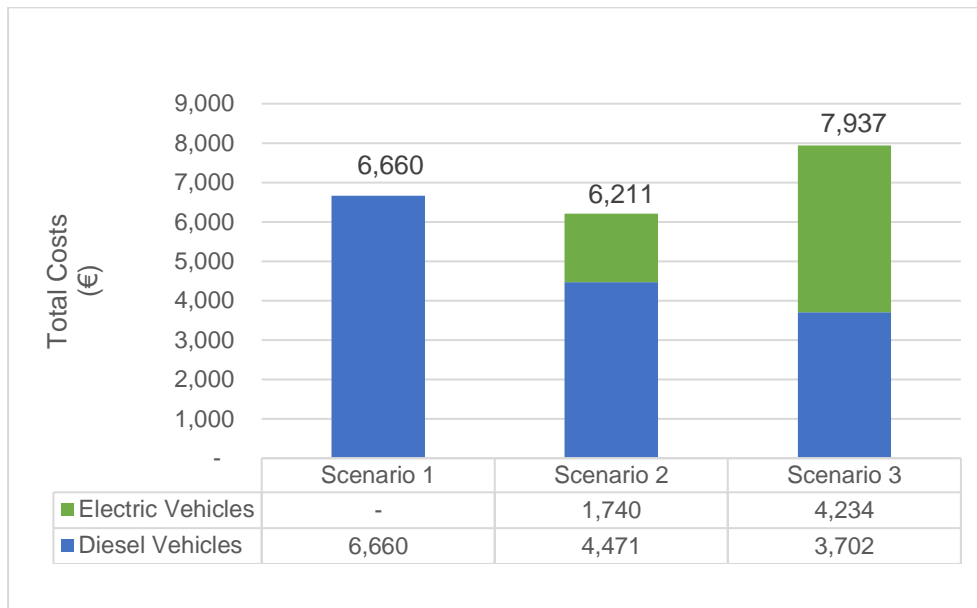

	Scenario 1	Scenario 2	Scenario 3
Electric Vehicles	-	1,740	4,234
Diesel Vehicles	6,660	4,471	3,702

Figure 5.8 Total Operating Costs

5.1.3. Environmental Impact Results

The emissions, calculated using emission conversion factors, are presented in this sub-chapter. Emission results of CO_2, CO, PM_{10}, HC and NO_x are evaluated in this sub-chapter.

5.1.3.1. CO_2 Emissions

Figure 5.9 shows the recorded CO_2 emissions for electric (kg/kWh) and diesel (kg/l) vehicles considered in this study as well as the combined emissions for both drivetrains in kilogram (kg). It is necessary to highlight that CO_2 emissions for electric vehicles are calculated using a well-to-wheel conversion factor which considers the CO_2 emissions generated during the generation of electricity supplied at the charging infrastructure.

Scenario 3 has the lowest CO_2 emissions, followed closely by scenario 2, with a 3kg difference between them. Scenario 2 and scenario 3 produce a significantly lesser amount of CO_2 emissions, both having approximately 30% reductions compared to baseline scenario 1. From the emission values recorded in Figure 5.9, it is observed that the implementation of sustainable measures, modelled in this research, has a significant impact on the reduction of CO_2 emissions.
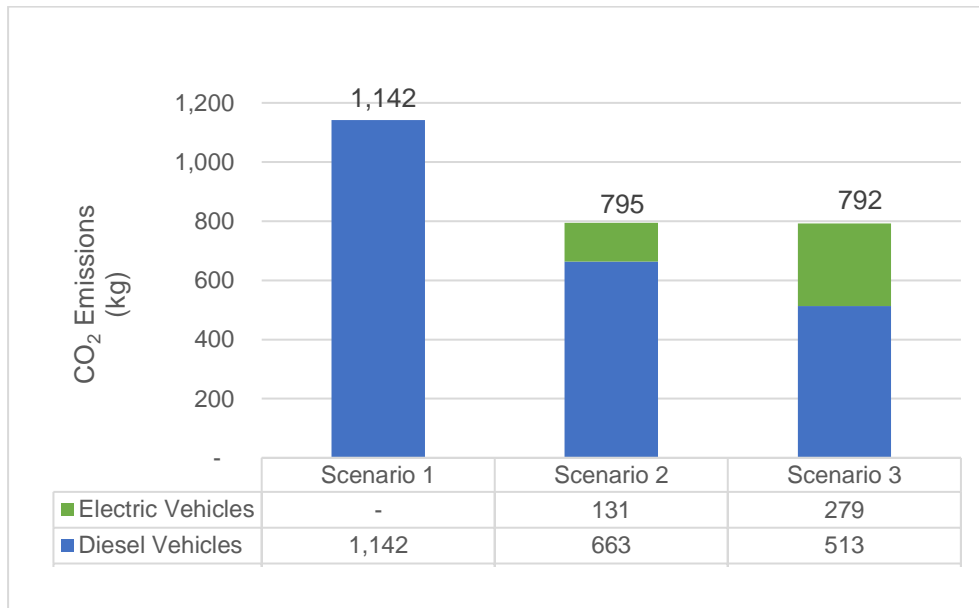

	Scenario 1	Scenario 2	Scenario 3
Electric Vehicles	-	131	279
Diesel Vehicles	1,142	663	513

Figure 5.9 CO2 Emissions

5.1.3.2. CO, PM_{10} and HC+NO_x Emissions

The quantity of air pollutants has also been determined, as one of the results of modelling environmental impacts in this study. The quantity of CO, PM_{10}, HC and NO_x emissions have been determined using emission conversion factors in gram per metre (g/m) and the total distance travelled by the operating vehicles.

It is necessary to point out that no air pollutants were recorded for the electric vehicles modelled in this study. This is because electric vehicles produce zero direct emissions. Emission values for HC and NO_x have been combined as one conversion factor is used to determine both emission types. The emission values for these emission types are presented in Figure 5.10.

The results show that significantly reduced emissions are obtained in scenario 2 and scenario 3, compared to scenario 1 for all emission types considered. These emissions recorded for scenario 2 and scenario 3 are solely from the diesel vehicles used in these scenarios.
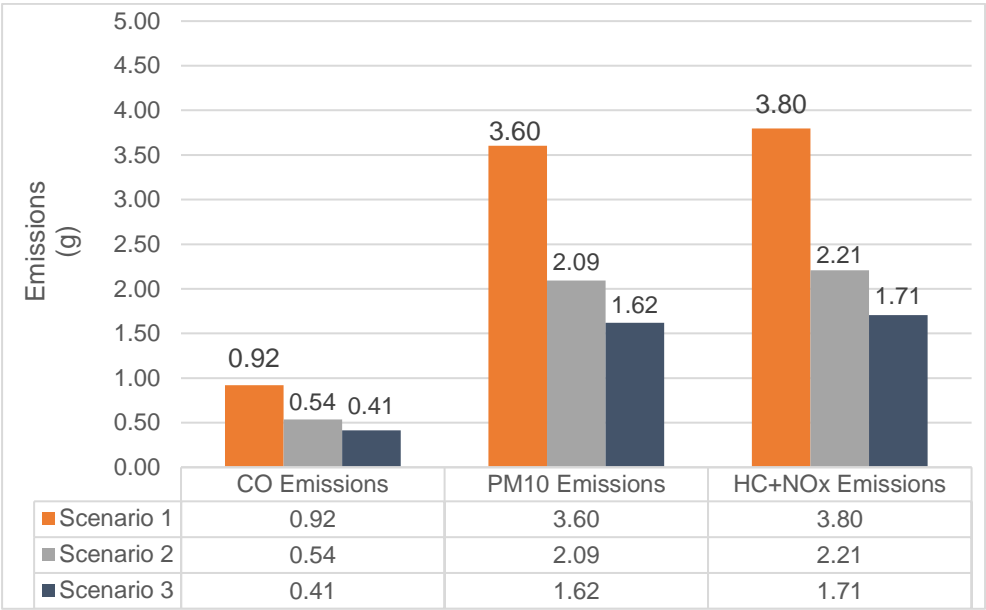
Figure 5.10 CO, PM$_{10}$ and HC+NO$_x$ emissions

5.2. Discussion

In the introduction of this research project, the goal of the research was to provide an answer to the scientific inquiry:

How does the implementation of policy, logistics and technological measures impact the volume of freight trips, emissions, and the operating costs of freight distribution in urban areas?

To tackle this question, this research has employed a multi-agent transport modelling approach to answer this question. Table 5.1 shows how this research question has been tackled. The question has been divided into 3 branches: freight trips, operating costs, and emissions, to sufficiently perform an evaluation of the research objective.

Table 5.1 Approach to the research question

Goals	Criteria	Indicators
1. Model the impact of policy, logistics and technological measures on the volume of freight trips	1.1. Total Vehicle kilometres travelled	1.1.1. Number of vehicles required 1.1.2. Average freight distance 1.1.3. Total freight distance 1.1.4. Fuel Consumption
2. Model the impact of policy, logistics and technological measures on operating costs	2.1. Transport Costs	2.1.1. Fixed costs 2.1.2. Variable costs 2.1.3. Personnel costs 2.1.4. Total costs
3. Model the impact of policy, logistics and technological measures on Emissions	3.1. Emissions	3.1.1. CO_2 Emissions 3.1.2. CO Emissions 3.1.3. PM10 Emissions 3.1.4. HC+NOx Emissions

To model the goals highlighted in Table 5.1, three scenarios have been developed to evaluate the impact of selected sustainable measures on urban freight distribution.

Scenario 1: A baseline scenario developed to serve as a benchmark for the selected sustainable measures.

Scenario 2: A case scenario, developed to model technological implementation of CEP service provider's partial fleet electrification (30%).

Scenario 3: A case scenario, developed to model policy implementation of a zero-emission zone,   logistical implementation of micro depots and selected electrification of CEP service provider's fleet.

To constructively assess the impacts of scenario 2 and scenario 3 based on the criteria outlined in Table 5.1, the results are compared to the baseline scenario in scenario 1, using indicators presented in Table 5.1.

A comparative assessment of the three scenarios is summarized in Table 5.2. For each indicator considered, the results obtained for scenario 1 is used as a benchmark for assessing the other two case scenarios. The assessment values are connoted in percentages, and the value of scenario 1 is depicted as 0%, indicating the benchmark. Improved results in scenario 2 and scenario 3 are denoted as positive percentages while declining results are denoted as negative percentages.

Table 5.2 Assessment of research indicators

Indicators	Scenario 1	Scenario 2	Scenario 3
Number of vehicles used	0%	-11%	-56%
Average freight distance	0%	25%	38%
Total freight distance	0%	18%	4%
Fuel Consumption	0%	35%	41%
Fixed costs	0%	-10%	-56%
Variable costs	0%	23%	16%
Personnel costs	0%	18%	6%
Total costs	0%	7%	-19%
CO_2 Emissions	0%	30%	31%
CO Emissions	0%	41%	55%
PM10 Emissions	0%	42%	55%
HC+NO_x Emissions	0%	42%	55%

In Table 5.2, all the indicators considered have a negative proportional relationship with the logistics system. This implies that an increase in the result recorded for an indicator will lead to a negative impact on the corresponding criteria within the logistics system. An improved result, denoted by a positive percentage, is inferred when the result, for the case scenario, is better than the benchmark in baseline scenario 1. A declining result, denoted by a negative percentage, is inferred when the result for the case scenario is worse than the benchmark in baseline scenario 1.

The number of vehicles used in scenario 2 and scenario 3 increased, compared to baseline scenario 1. This has been attributed in the lower loading capacity of the electric vehicles modelled for scenario 2 and scenario 3. The increase in vehicles used could also be associated with the combined delivery function, used in the model, which might not adequately depict the logistics optimization used by CEP service providers. This increased vehicle utilization could be remedied by further optimizing the way deliveries are handled, to allow the best possible usage of the fleet.

The fixed costs for scenario 2 and scenario 3 are also worse than the results for scenario 1. This is because fixed costs directly depend on the number of vehicles used. A reduction in the number of vehicles used for scenario 2 and scenario 3 will result in much-better fixed cost values which will, in turn, improve the overall total cost.

However, for other results independent of the number of vehicles used, the improvements recorded are very significant. For the average distance travelled indicator, the results recorded for electric and diesel vehicle types in scenario 2 and scenario 3 have been averaged to obtain an average distance for all vehicles used. From Table 5.2, at least a 25% reduction in average distance travelled by each vehicle is recorded for the sustainable scenarios modelled.

For the total freight distance indicator, a reduction of 4% is recorded for scenario 3. While this percentage reduction could be considered not substantial enough, it shows that the two-step distribution (distribution centres to micro depots to recipients) does not necessarily increase the total distance travelled.

For emission results, scenario 3 recorded a 55% reduction in air pollutant emissions, while scenario 2 recorded about 41% reduction in air pollutant emissions. Also, a 30% reduction in CO_2 emissions was recorded for scenario 2 and 31% reduction for scenario 3. The significant reductions recorded in emission levels is attributed to the increased use of electric vehicles.

The scenarios with implemented sustainable measures currently have higher vehicle utilisation. However, this can be further optimised to allow the best possible usage of the fleet. Considering this, the high fixed costs recorded is not seen as a discouraging factor for the implementation of the sustainable measures illustrated in scenario 2 and scenario 3. Furthermore, the improvements recorded in scenario 2 and scenario 3 significantly outweigh the declines. Thus, this research has not been able to prove that significant improvement in operating costs could be obtained from implementing sustainable measures in urban freight distribution. Nevertheless, the results recorded in this research point towards the notion that implementation of sustainable measures, as modelled in the case scenarios, can produce significant positive impacts on vehicle distance travelled and emission levels.

The next chapter discusses the conclusions derived from the results and recommendations for further research.

6. Conclusion

This research demonstrates that the implementation of policy, logistical and technological measures have a significant impact on the reduction of freight distance travelled and the reduction of emissions produced from urban freight distribution operations. Total distance travelled by freight vehicles recorded a reduction of at least 4% while average distance travelled by each freight vehicle recorded a reduction of at least 25%. CO_2 emissions recorded a reduction of at least 30% for the case scenarios modelled. Air pollutant emissions, consisting of CO, PM_{10}, HC and NO_x recorded a 41% reduction from the partial implementation of vehicle electrification and a reduction of 55% from the implementation of low-emission zones, micro depots, and partial fleet electrification. Costs attributed to fuel consumption also recorded a reduction of about 35%.

This research was, however, not able to demonstrate that, the implementation of sustainable measures could achieve a reduction in operating costs for logistics service providers in the courier, express and parcel (CEP) industry. Of the two case scenarios modelled, only the scenario with partial fleet electrification recorded a reduction in the operating cost of a CEP service provider. The other case scenario, which implemented low-emission zones, micro depots, and partial fleet electrification, recorded a substantial increase in total operating costs by 19%. This increase is attributed to the high fixed costs recorded for this scenario. It has been established that an optimization of the use of vehicles could enhance efficiency and reduce the total operating costs.

Ultimately, the results obtained from this study indicate that the implementation of sustainable measures in urban freight distribution could potentially reduce vehicle distance travelled and emission levels associated with urban freight transport operations.

6.1. Limitations of this research

The main limitation of this research is its inability to fully consider the total freight demand for the city of Berlin due to a lack of computational power to handle large datasets. Since agent-based modelling requires consideration of each actor in the modelling environment as an individual agent, the performance of the model was extremely poor with the reported freight demand of Berlin. This research could only handle 3% of the total demand recorded in an earlier study by Thaller (2018). Hence, the results obtained in this study is not entirely a basis for decision making. While the research methodology

has constructively answered the research question, the consideration of the entire reported freight demand would provide a sufficient basis for policy and operational decision making.

Another limitation of this research is that it does not consider the choice between different CEP service providers. This research assumes that all distribution centres in Berlin belong to the same CEP service provider. This assumption was made to achieve the development of a model within the timeframe permitted for this research. Consideration of different service providers in the development of the model requires significantly longer development time, more data and more computational power. In a realistic scenario, the assumption that all distribution centres belong to the same service provider is usually not the case. There are usually different service providers serving an urban area as big as Berlin.

Furthermore, the limited availability of information regarding the intricacies of logistics operation is also a limitation of this research project. The model developed for this research applies a combined delivery function within its demand preparation module. This function is applied as a delivery optimization function to simulate combined delivery to a link on the network. This function is borne out of the limited knowledge of how actual logistics optimizations are performed by service providers. Logistics optimizations are the competitive edges used by service providers, hence, they are considered confidential business information. Limited information about the intricacies of these logistics operations will continue to slow down the development of advanced freight transport models.

6.2. Recommendations for Further Research

1. Consideration of total freight demand

   It was earlier stated that this research project could not consider the total freight demand reported by Thaller (2018), due to low computational power. Hence, this research recommends that a more comprehensive freight demand should be considered to arrive at conclusions that form a sufficient basis for policy or operational decision-making.

2. Consideration of different service providers

   This research assumes that all the distribution centres modelled for the city of Berlin belong to the same service provider. This does not reflect the actual situation of courier, express and parcel (CEP) operations in Berlin. A recommendation for further

research would be to consider a scenario with a more accurate depiction of CEP service providers, considering several providers.

3. Location of Micro Depots

   In this research, micro depots have been implemented as a sustainable measure by logistics providers. However, this research did not consider how the location of the micro depots was decided from a logistics perspective. This research has been able to demonstrate that micro depots are a viable measure to achieve a reduction in emissions and total distance travelled. It is therefore recommended that further research be carried out to determine the optimal locations for micro depots.

4. Implementation of other sustainable measures

   Several sustainable measures have been discussed in 2.3 of this text. However, not all of them have been implemented in the scenarios modelled. It is recommended that the impact of the other sustainable measures discussed should be modelled and evaluated. The methodology applied in this research could be applied to modelling other sustainable measures.

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Declaration concerning the master's Thesis

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.

Munich, July 31st, 2020

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